GUGGENHEIM MEMORIAL LECTURE

DEVELOPMENTS IN FLIGHT GUIDANCANCE AND CONTROL

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Keywords: *Flight Guidance, Satellite Navigation, Wake Vortices, Aviation Safety, Turbulence*

Introduction

Guidance and control of aerospace vehicles is an interesting and multidiscipline subject. The scope of the interest involves branches like aerodynamics, meteorology, flight mechanics, control theory, flight control, flutter control, engine control, air traffic control, sensor dynamics, computer science, man machine interface as well as technologies as aircraft design, sensor and computer design, micro mechanics and electronics. This complete description of the subject `Flight Guidance and Control´ cannot be mastered by a single person alone.

As an introduction I will give an overview of the historical development. This again is incomplete and in some details related to my personal point of view. My target is to discuss the different subjects and disciplines in a context. We can access research activities in some disciplines for more than 200 years and also the state of the art level of investigation and knowledge in aeronautics is extremely high, there are many gaps that has to be completed with additional research. I will focus my interest on some specific scientific problems (flight in turbulent air), aviation safety problems (windshear, design of safety critical flight control systems), technological problems (use of satellite navigation for safe airplane operation including some political aspects), and last but not least on economical problems (improved airport capacity, efficient air traffic control).

1 Overview on Historical Development

Guidance and control is an essential part of an aircraft and the history is as long or even longer as the aircraft history.

In the very beginning of the aviation was the aim to bring a flying machine into the air. Lack of excess power as well as insufficient stability were major obstacles. Probably the first who arranged a stable flight of a powered but unmanned airplane was Alfonse Pénaud in 1879. The propulsion of this small model airplane was realized by a twisted rubber that forced a propeller. This airplane was equipped with fins for a stable flight. The flight was successful but Pénaud was not accepted in public, the people laughed at him. He committed suicide in the same year.

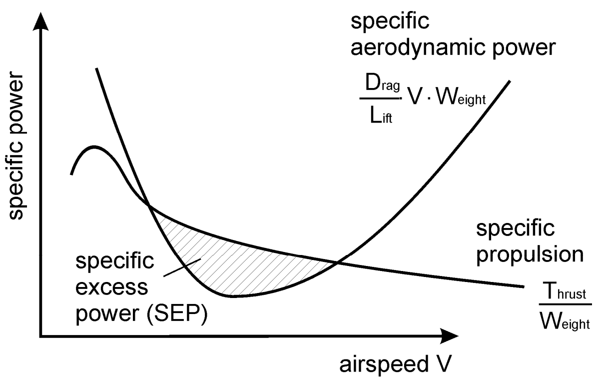

Figure 1: Penaud diagramm

Pénaud is to my mind the father of flight mechanics. The famous Pénaud diagram (figure 1) demonstrates the specific excess power as a difference of aerodynamic power and propulsion power. Aerodynamic power is the drag to lift ratio multiplied by weight and speed. All important flight performance parameters are involved. In the following decades a lot of effort has been made to reduce the weight of the aircraft and to increase the propulsion power.

The first manned but non-powered flights were realised by Otto Lilienthal in 1891. Lilienthal pushed the knowledge in aerodynamics a big step forward. The Lilienthal gliders were unstable in the sense of flight mechanics and very difficult to control, especially in turbulence and gust. The fatal crash in 1896 was primarily based on the poor control of this type of aircraft in turbulence and gust. The critical response of aircraft in turbulent atmosphere is known as a severe problem since Lilienthal's flights. A lot of successful investigations have been executed in the meantime. But there is still a lack of knowledge and further scientific investigations would be worthwhile. I will discuss this later in this lecture.

Gustave Whitehead in Pittsburgh, Pennsylvania, in 1899, had prepared the first powered and manned flight. The aircraft was powered by a steam engine. In 1901 Whitehead realized flights with gas engines.

The Wright brothers started their first manned powered flight in 1903 and this was the breakthrough of aviation in public opinion. A very important invention was the use of ailerons and elevator for the control of the roll and the pitch axis by aerodynamic means. The Wright brothers' flying machine had marginal excess power and again was difficult to control in turbulent and gusty weather conditions.

Parallel to the development of aerodynamics, lightweight structures and aero-engines, the investigations in sensors took place. As the excess power varies very strongly with airspeed (figure 1), the proper control of airspeed even in the early days of aviation was mandatory. The sound of the string wires (also known as '*flying wires*') in the air stream gave a good indication of the airspeed. The dynamic pressure disc (figure 2) realized the visual indication of airspeed.

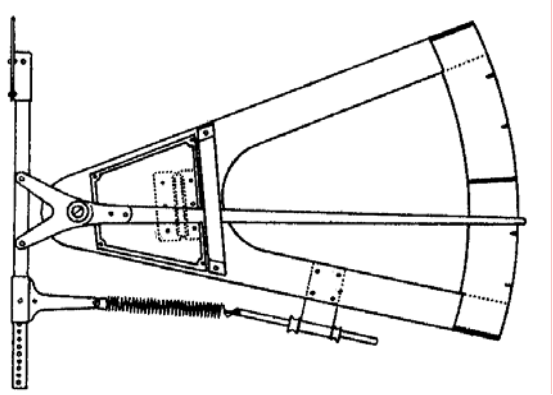

Figure 2: Dynamic pressure indicator

Many of the sensors used in an airplane were taken over from other disciplines, especially from steam engines and ships. With the introduction of the steam engine automatic control became more and more important. The first steam engines were operated with manual valve control. Young boys had to do this boring job. Humphrey Potter coupled the swinging beam of the steam engine with the valve via ropes in 1713. James Watt had invented the speed control of steam engines at the end of the 18th century. A rotating pendulum controlled the valve to adapt the pressure in the engine to maintain the engine speed. Watt's basic idea behind this automatic controller was to improve the safety of the engine operation and to increase the accuracy, as in his mind, an automatic control is always more reliable and precise compared to a human operator. This basic idea can be adapted seamlessly to aircraft operation. In the beginning of the 19th century excellent theoretical progress has been made in the dynamics of perpendicular rotational speed controllers. On this basis of sensor dynamics the theoretical principles of control systems have been developed in the following 200 years.

Independent from practical aeronautical application, important physical fundamentals have been studied. Sagnac's (1913) experiments to determine the speed of light are the basis for fiber-optical rate sensors and laser "gyros" as well as for satellite navigation and RADAR (RAdio Detection And Ranging) sensors. Heinrich Hertz experimented with the reflection of electromagnetic waves on walls and obstacles in 1886.The RADAR principle has been patented by Christian Hülsmeier in Germany in 1904 and by Hugo Gernsback in US in 1911.This RADAR principle had been applied by Marconi in 1922. The full break through of this principle came with the beginning of the 2nd world war. RADAR development is a good example that excellent ideas need a lot of time for evolution. This is noteworthy since the typical lifetime of a patent is roughly only 20 years.

The ideas of James Watt for automatic control were adapted to airplanes by Lawrence Sperry in 1911 (figure 3). Inertial gyros are the basic sensors to control the rotational axis. A proper control theory to design the control system was still not available. A good engineering feeling as well as trial and error approach was a simple but successful tool to design control systems.

Figure 3: Sperry's automatically controlled flight (1911)

Long duration flights were the target for many aviators in the beginning of the 20th century. The theoretical background was prepared by Louis Charles Breguet (1910) and his famous range formula involved all relevant flight performance parameters.

$$R \propto \frac{V}{b}\frac{C_L}{C_D}\ln\left(\frac{m_a}{m_e}\right)$$

Bleriot's flight across the English Channel (1909) was a milestone in aeronautics. But it raised legal and political discussions concerning the ownership of the national airspace. Is air traffic more *international sea orientated* or more *national land orientated*? The basic for solutions have been prepared 40 years later in the Chicago Convention in 1944.

During the 1st World War, the development of aviation was enormous. The airplanes became more powerful, faster and heavier, and load as well as range increased significantly. The industrialized countries learned to produce airplanes in great quantities. The airspace became more and more crowded. In 1910 four midair collisions had already been reported. This risk increased and has been increasing so far.
The lack of trained pilots to equip the high quantity of airplanes became evident. Flight simulators for the basic training of student pilots had been developed (figure 4).

Figure 4: Franz Drechsler's flight simulator (first world war)

The further progress of flight simulators was orientated on the status of the technical evolution (figure 5). Today's flight simulators give the pilot a high fidelity feeling to fly in a real aircraft. The today's digital computers are powerful enough to be the basic for excellent dynamic models, instrumentation, artificial vision and motion.

Figure 5: Modern training flight simulator

The demands for artificial vision systems are extremely high, as the natural human vision system is excellent. In the past, simulated flights under poor visibility were much easier to realize compared to those in brilliant visual conditions. The first acceptable visual systems were based on a camera, which flew over a scaled modeled terrain. The position of the camera and its orientation were related to the calculated aircraft situation. The simulator motion system is limited in translational range due to costs. Five meters translational range for a motion system is upper standard. With a proposed acceleration of 1g, the five meter limit will be reached within one second. As the human being has a wash out behavior in the acceleration feeling and cannot distinguish between translational acceleration and earth acceleration, the long-term acceleration impression can be realized by rotating the simulator-cabin. Thus, the pilot's impression of acceleration for transport aircraft is sufficient. For high agile combat aircraft special solutions are necessary. This wash out procedure works well with medium quality visual systems. However, some highly sensitive pilots have trouble to coordinate the limited acceleration feeling with excellent artificial vision and become seasick.

After the 1st World War, many military aircraft were available that could be modified for mail and passenger transport. In 1919 a commercial scheduled airline between Berlin and Weimar had been established. In the same year the first scheduled international flight from London to Paris had been introduced. With scheduled air traffic a safe navigation was required for all weather conditions. Before the 1st World War, airships (Zeppelin) were used for long-range passenger and cargo flights. The navigation, the instrumentation, control wheels and even the uniforms of the crewmembers were maritime-orientated (figure 6).

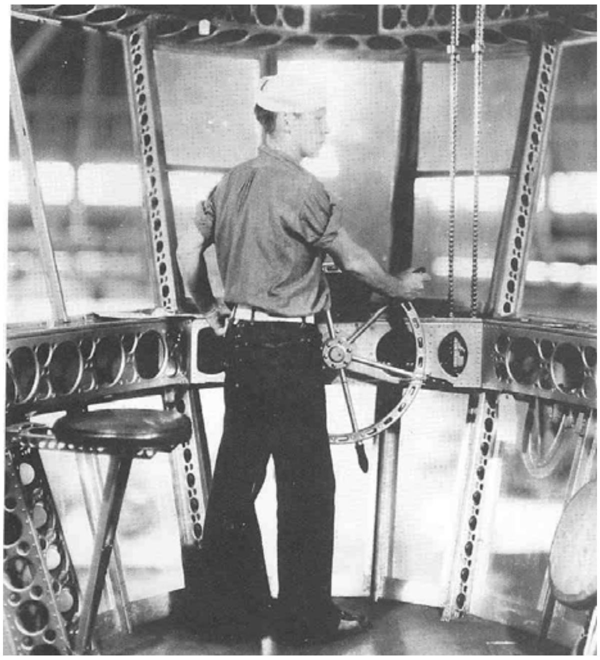

Figure 6: Airship cockpit (Zeppelin)

The ship-orientated navigation was applied with minor modifications. Landmarks and lighthouses helped the pilot to navigate. In a big midair collision north of Paris between a French and a British aircraft in 1922 seven persons were killed. This accident aroused public discussion of air safety and resulted in the adaptation of a precursory airways system. Pilots on the busy London/Paris air route were instructed to remain west of the direct route when flying towards London and east when flying the route in the opposite direction.

Increasing air traffic required an international standardization of procedures: legal, technical as well as commercial. Six European airlines formed in 1919 the International Air Traffic Association (IATA) to help the airlines to standardize their paperwork. The British legislation was the which introduced the activities of the aviators into a legal framework.

In 1916 radio-communication was introduced in ground stations and airplanes. The forerunner of air traffic control had been established. The improving knowledge in high frequency radio range techniques was used for position finding and navigation of airplanes. Direction finding by radio beacons and beams improved the situation in poor visibility. The British government warned private pilots without wireless communication to keep clear of routes used by commercial aircraft in bad weather.
The increasing air traffic required safe procedures especially in bad weather conditions. Heinrich Koppe, the founder of the Institute for Guidance and Control at the Technical University of Braunschweig formulated his vision of all-weather flight in 1925. Roughly 30 years later his vision was realized in practice.

In the beginning thirties Ernst Kramer from the Lorenz Company developed the principles of the Instrument Landing System (ILS). A radio beam in runway direction with a slope of the aircraft approach angle could guide an aircraft without visibility. Radio beacons gave a rough distance measurement to the threshold of a runway (figure 7). This system had been installed in Germany in the early thirties and since 1936 in Great Britain (Croyden Airport). Traffic density results in aerodrome control zone and adaptation of specific procedures to maintain safe separation. In 1935 IATA called for a standardized system of aircraft landing aid. The worldwide standardization of ILS took place under the aegis of ICAO in the early fifties.

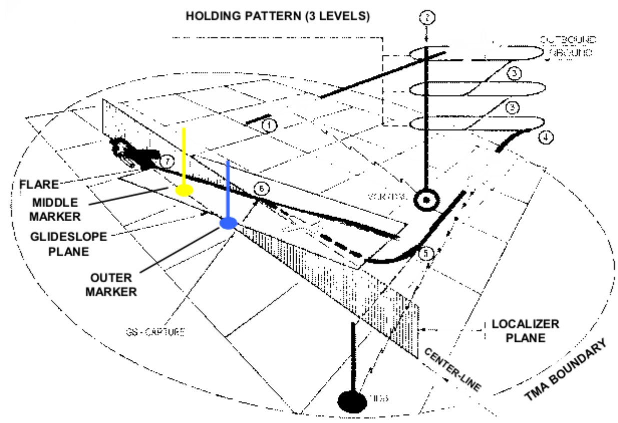

Figure 7: Instrument landing system

Just before or during the 2nd World War famous technical inventions have been made. The turbo-engines developed by von Oheim in Germany and Whittle in Great Britain (both successfully bench-tested in 1937) changed the world of aviation, first military and then civil. With the additional invention of the swept wing in Braunschweig and Göttingen (figure 8,9), a new generation of high-speed airplane has been developed.

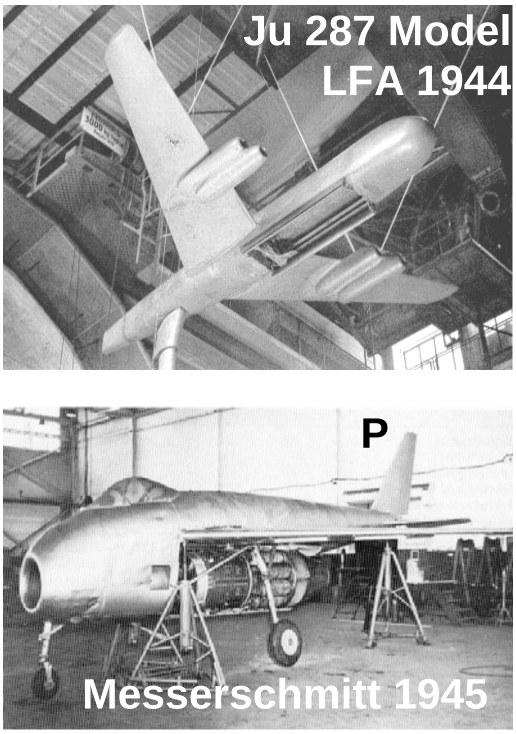

Figure 8: Swept wing aircraft for high subsonic speed reduced compressibility effects

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Figure 9: JU-287 in flight

The first high speed subsonic civil transport aircraft was the Comet (figure 10) with its first flight in 1952. In 1958 subsonic flights were state of the art (DC8, B707, TU-104) and a new area of civil transport began

Figure 10: De Havilland Comet (first commercial subsonic jet aircraft)

Even before the 2nd World War was over, representatives of the allied nations set the rules for commercial aviation in what was expected to be an era of growth encouraged by the use of now existing technologies. In the resulting Chicago Convention of 1944 the standards and recommended practices, contained in a series of annexes, establish rules on every aspect of civil aviation including the development and conduct of air navigation and air traffic control. This formed the basis of present day Air Traffic Control (ATC) throughout the world.
Airways were established in US and Great Britain. The International Civil Aviation Organization (ICAO) was officially established in 1947 on the basis of the Chicago Convention.

Ground controlled approaches (based on precision RADAR) were introduced in military flight in the US. The commercial use had only a short lifetime because it was difficult to handle. A human ground controller and the pilot have to communicate precisely and without significant time delay and thus ILS became dominant.

IATA and ICAO formed international rules to establish Air Traffic Management (ATM) in the beginning fifties. One driver was the rising amount of commercial high-speed subsonic transport aircraft. The typical airspeed of such an aircraft is 300m/s. A human pilot can identify an oncoming aircraft at excellent visual conditions in a distance of 3 km. The time remaining between identification and potential midair collision is only 5 seconds.

The basic concept of air traffic control is to measure the position of the aircraft by a precise ground RADAR. The today's generation of secondary RADAR uses the aircraft as a transponder, where actual barometric height and the aircrafts' identification number is provided in the answer of the transponder to the initial RADAR signal. The ground ATC has all relevant airplanes visible on a RADAR screen. Additional anti-collision systems use RADAR contacts between two or more aircraft. Procedures have been developed for automatic anti-collision tracks. But this safe system can be overridden by the human being (pilot or ground controller). The fatal accident in Überlingen, lake Constance (2002), where two transport aircrafts crashed midair was a sequence of misunderstandings. Without human interference both aircraft would have continued their flight safely. The priority between pilot, ground controller and automatic system is clear in principle. But still a lot of additional research has to be invested in this critical man-machine-interface.

The introduction of Air Traffic Control (ATC) and the national control organizations and the daily operation of the system is expensive. It was internationally agreed that air traffic fees should cover those costs. Since 1952 the passenger-mile and the ton-mile were the calculative units. The air traffic cost including landing fees are on the same level as the fuel costs (figure 11). There is a strong tendency to deregulate the air traffic and to privatize the national air traffic control organizations to reduce the costs.

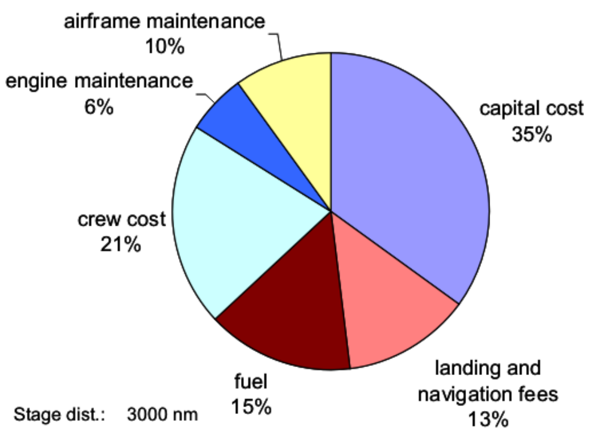


Figure 11: Direct operating costs

The increasing air traffic over the North Atlantic Ocean required a safer separation and long-range navigation aids such as LORAN and CONSOL were developed. These low frequency radio navigation aids were basically invented for marine navigation, especially submarines.
Inertial Navigation has been developed first for medium range missile application in Germany (A4 rocket) in the late thirties.
Inertial Navigation is very simple in principle (figure 12). The acceleration of the aircraft has to be measured and integrated first to aircraft velocity and then to aircraft position. The position error increases with time. The major effort in the reduction of the errors (roughly 90%) has to be spent on the leveling of the acceleration sensors in order to eliminate the influence of earth gravity. The idea of Schuler (1924) giving the inertial platform the same behavior as a pendulum of the length of the earth radius (oscillation time of 84,4 minutes) makes the inertial platform independent from aircraft acceleration and suitable for long range navigation.

Typical transport aircraft as the Boeing 747 had installed three parallel inertial navigation systems for long-range navigation. The precision of the inertial navigation was good enough for separation distances of 60 miles. The 1000 feet vertical separation was realized by standard static pressure measurement.

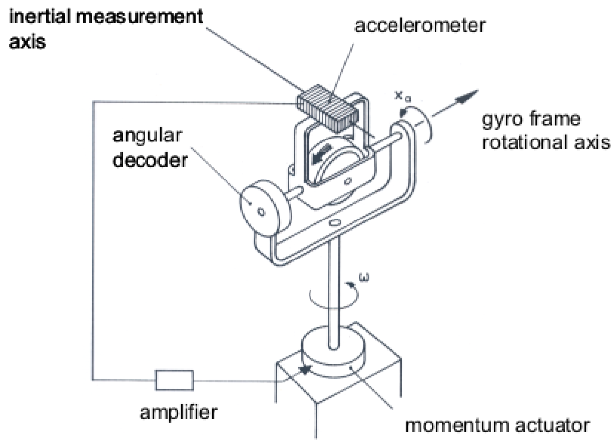


Figure 12: Basic principle of inertial navigation (single axis)

Digital Computers became more and more powerful since its invention by Konrad Zuse in 1938. The first computers established in air traffic management were big and power consuming machines. Since 1970 digital microcomputers are fast enough to solve onboard problems, for example air data computing, flight control, data processing, symbol generators in visual systems, etc.

The development of television screens gave the initiative to introduce electronic displays in airplanes. Starting with military applications in the seventies, Airbus introduced electronic displays in the cockpit of civil airplanes (figure 13). The amount of conventional displays and indicators has been dramatically reduced by electronic displays (compare figure 14).

After some controversy discussions the new generation of pilots has accepted its new role as a manager of an airplane and as a part of this, the electronic displays.

Figure 13: Glass cockpit and side stick control (Airbus A320)

Figure 14: Lockhead Super Constellation (1951)

From the very beginning of aircraft design the reduction of structural weight was an enormous problem. Design of lightweight structures has become an own discipline. New materials as fibre material help to reduce the weight but will change the dynamic structural response of an aircraft. The design of a control system has to keep this in mind.
In military fighter aircraft, structural weight is even more essential compared to civil transport aircraft. Due to an increase in maneuverability and agility the response time for maneuvers had significantly to be reduced. The conventional control rods and ropes became too weak and too heavy. An electrical or a light signal to link the control column and control actuator (fly by wire) was the solution.

After a decade of experience in military and the Concorde aircraft (figure 15), Airbus decided the Fly-by-Wire concept was safe enough to be introduced on wide-bodied civil transport aircraft (Airbus A 320, figure 13) in 1987. This was a bold step at the time, but the effort proved successful and the technology is now state of the art.

Figure 15: Concorde (1969)

The newest important invention in aviation that shall be considered in this historical overview as well as a technology subject in this lecture is satellite navigation.

Satellite Navigation

The American GPS and the Russian GLONASS are available since 1989 after a successful development of more than 15 years. Both systems are nearly identical. Besides the design of aircraft and re-entry vehicles, this is probably the result of excellent intelligence services on both sides of the Iron Curtain during the Cold War. Both satellite systems are excellent in technical innovation as well as in the management of the development of huge technical systems. The new European GALLILEO satellite navigation is very similar to GPS and GLONASS, but its major advantage is its civil control in contrast to GPS and GLONASS, which are military controlled.

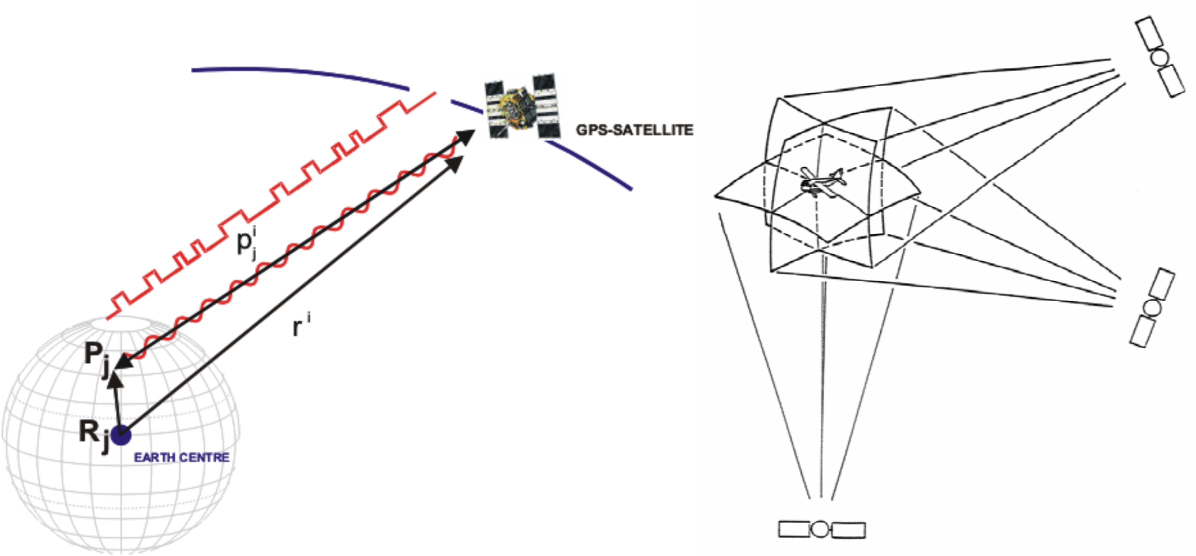


Figure 16: Basic principle of satellite navigation

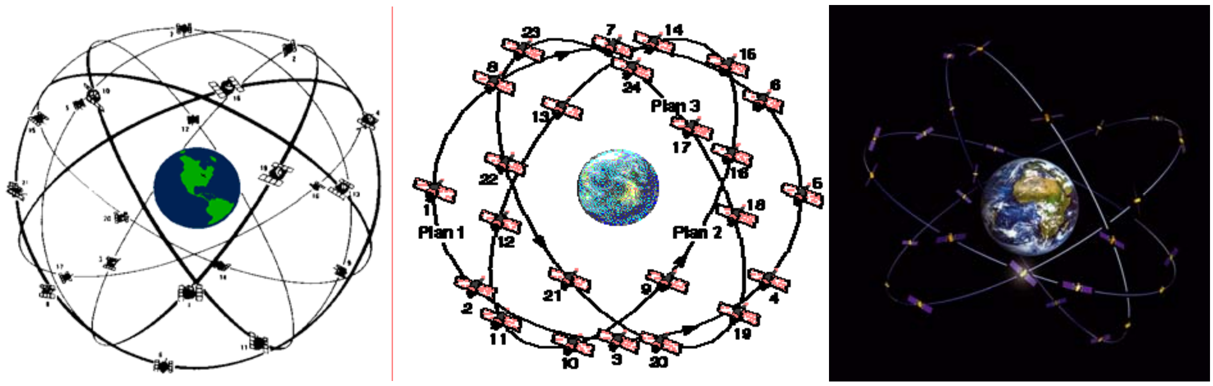


Figure 17: Orbits of GPS, GLONASS and GALILEO

The physical principle of satellite navigation (figure 16) is very simple. The satellites transmit a signal that travels with the speed of light. The transmitted electromagnetic signal is coded basically with a satellite identifier, the satellite position, the transmission time of the signal and some long term correction and identification parameters. The US system GPS presents the satellite position on the basis of Kepler parameters in contrast to the Russian system GLONASS, where the satellite position is directly presented in earth centered coordinates. These transmitted microwave signals will be received in a high gain microwave receiver onboard the vehicle. The range between satellite and vehicle can be calculated from the signals' traveling time multiplied by the speed of light. The traveling time is the time difference measured by two precise clocks, one in each satellite and one in the vehicle.

The accuracy of the time measurement is strongly depending on the quality of the time reference of the receiver. A similar expensive atomic clock is necessary for the satellite transmitter as well as for the receiver. With a minimum of three visible satellites the range measurement can give the basis for the calculation of the vehicle's three-dimensional position (figure 16). An additional time measurement to a fourth satellite can identify the clock errors and the precise atomic clock in the receiver becomes unnecessary.

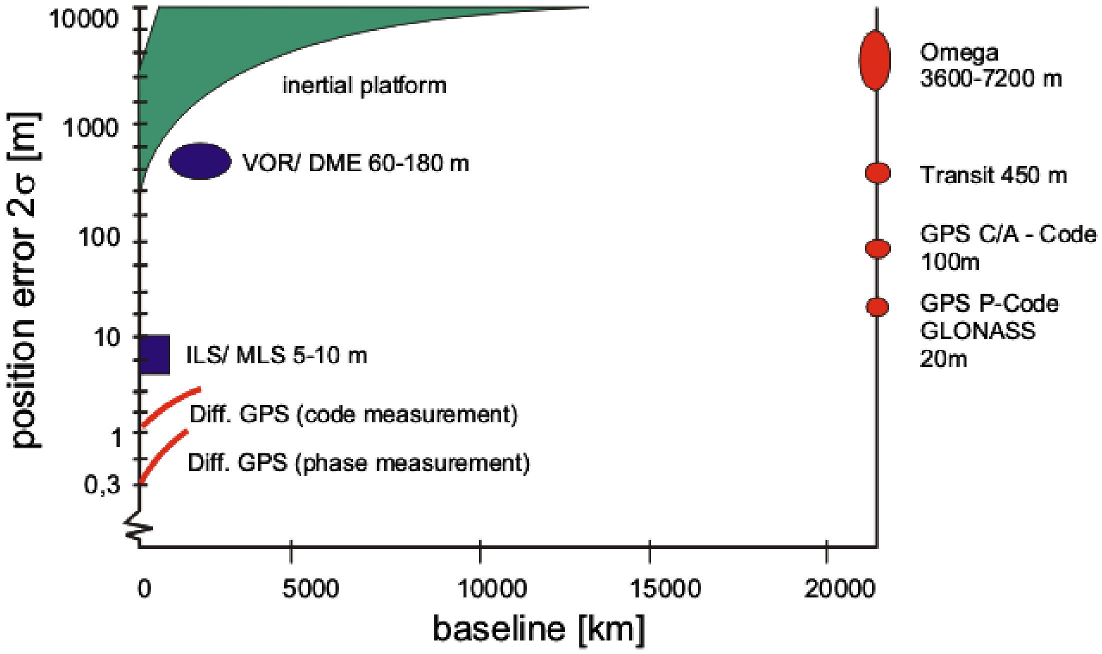


Figure 18: Comparison of navigation systems

With state of the art micro-electronics, the core of the satellite receiver can be manufactured at a cost less than 5 euro. Each satellite navigation system requires at least 24 operational satellites in the orbit to assure that a minimum of 4 satellites is visible simultaneously (figure 17).

For redundancy up to 30 satellites are in orbit for GPS and the same value is proposed for GALILEO. Due to economical problems in Russia, GLONASS is not fully equipped with satellites and is only limited operational. The demonstrated accuracy of GPS and GLONASS is in range of 15-20 meters, world wide (figure 18). This achievable accuracy is a revolution in navigation compared to the existing radio navigation systems and comparable to inertial navigation.

Satellite navigation is extremely precise. The world wide high navigation precision on the basis of satellite navigation for everybody was judged to be not acceptable by US government and an artificial reduction of accuracy was introduced in 1990 for civil use (SA: selective availability). The resulting degraded accuracy of 100-200 meters was still an enormous advantage but it was too low for precision “all weather” approaches.

Using the differential principle, even that problem can be solved. A fixed based reference receiver can find its own position within minutes with millimeters accuracy by methods that are state of the art in the geodetically community. All measured deviations in position or range could be defined as errors (figure 19).

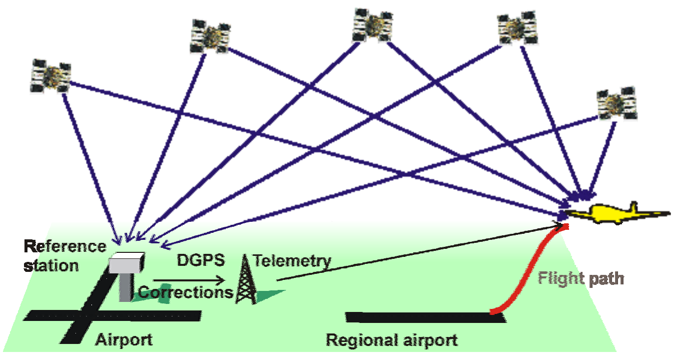


Figure 19: Differential satellite navigation principle

If these errors are transmitted to the movable receiver, the relevant onboard errors can be eliminated and the navigation accuracy can be improved significantly (figure 20). For operational applications, a baseline of 100 km is acceptable for CAT III weather minima operation. A baseline of 500-1000 km guarantees CAT I weather operations.

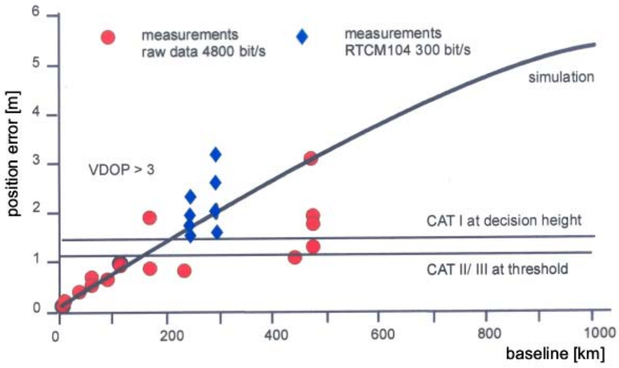


Figure 20: DGPS vertical accuracy

The coded satellite signal will be carried by an electromagnetic wave of a wavelength of 20 cm (figure 16). These waves can be counted and a resulting position accuracy has a potential of 0,1 mm. An accuracy of 5 cm is state of the art. This phase measurement has an unknown ambiguity (the integer values of the number of phase lengths) that has to be calculated. The procedures to solve the ambiguity problem are more or less known even for real time application.

The extreme high accuracy creates some philosophical, political and practical problems. As this high accuracy is available independent from the artificial reduction of accuracy, the selective availability made no practical sense and has been turned off in the year 2000. Position accuracy can only be related to a reference body. In general the earth will be simplified as a globe, but in reality there are many local and time variable deviations e.g. tidal effects, which have to be taken into account (figure 21). The definition of world geodetic system (WGS 84) in 1984 is still the reference.

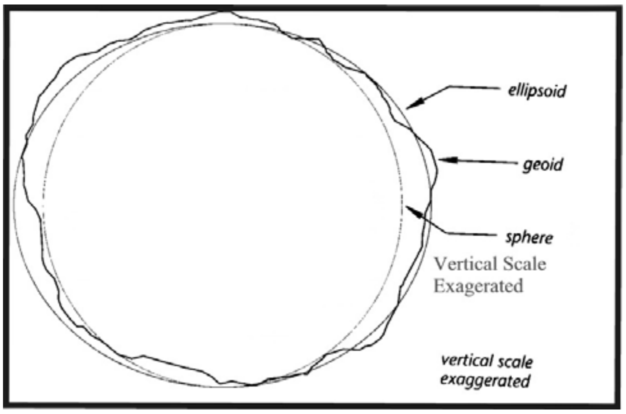


Figure 21: Earth’s Surface and its Modeling

Satellite navigation is extreme precise and facilitates a world wide position finding, but the signal is unreliable. The signal travels over a distance of more than 20000 km and will be influenced by the atmosphere. Any obstacle that interrupts the visual connection between satellite and receiver antenna will initiate a loss of the individual signal information. Obstacles can be parts of the airplane, buildings, and trees and in the worst case a tunnel.
The satellite signal is of extreme low power after the long propagation distance from the satellite. The signal power is below the level of natural signal noise. The signal can be disturbed easily by any interference. Especially surface transmitter with a wide power spectrum can corrupt the satellite signal totally. Low power transmitter of 1 Watt or less in the hand of terrorists can disrupt the satellite navigation totally in range of kilometers. With this safety critical behavior, stand-alone satellite navigation has not the potential for safety critical applications.

This is true for each of the three implement-tations of satellite navigation systems due to their physical principle. These problems can be overcome, if the precise but unreliable satellite navigation will be combined with a complementary system that must be reliable for short-term application periods. For this complementary system long-term high precision is not required. For aviation application low cost inertial navigation may be the ideal candidate (figure 22).

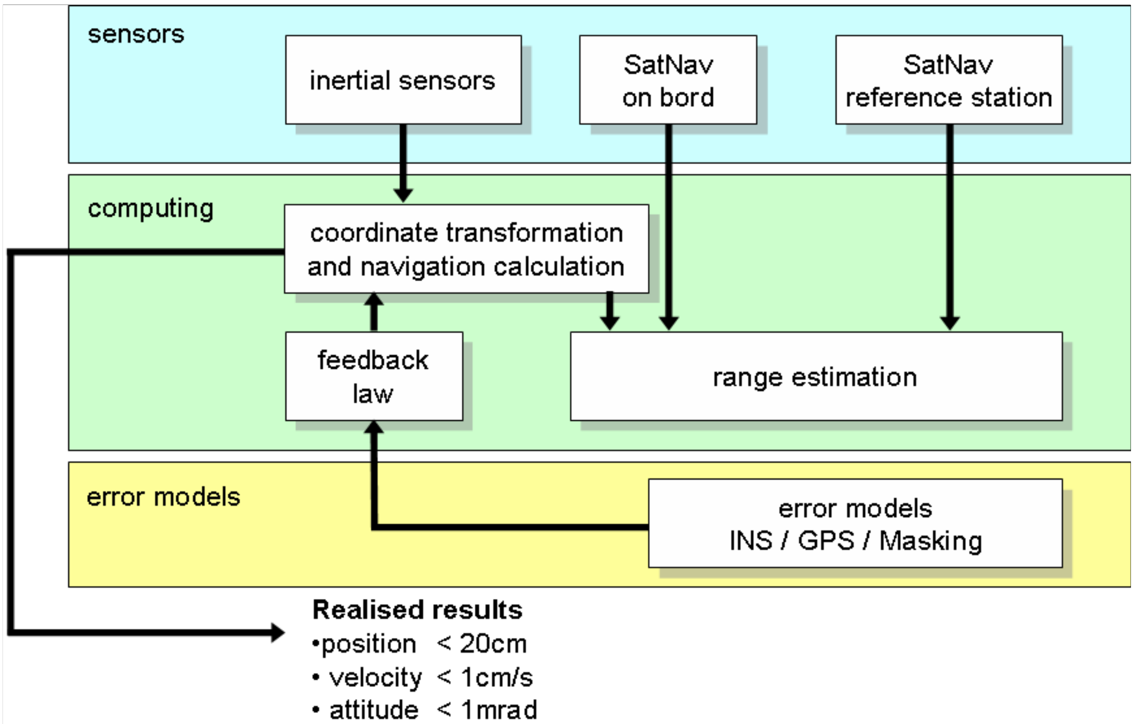


Figure 22: Integrated navigation system

It is the task of the system designer that the advantages of both the satellite as well as inertial navigation will be combined and the disadvantages of both will be suppressed.

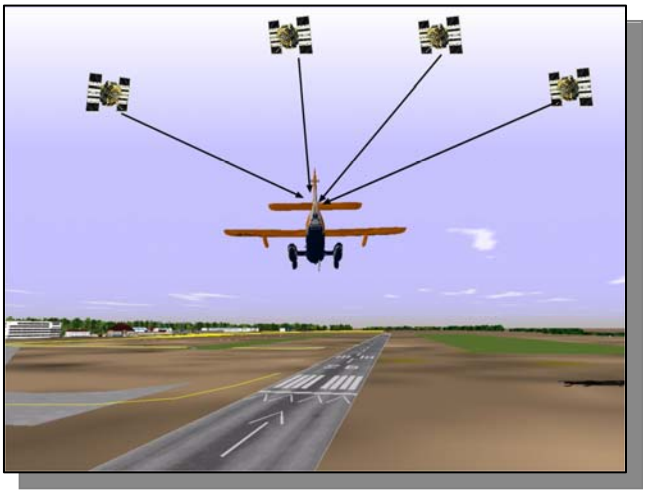


Figure 23: First worldwide automatic landing based on satellite navigation in Braunschweig 1989

With this type of precise position finding system the first automatic landing has been demonstrated during a symposium of the German Institute of Navigation in July 1989 at Braunschweig airport by the Technical University (figure 23). This was the first time that four GPS-Satellites were visible at noon for roughly one hour.

The advantage of satellite navigation for aerospace application will be enormous, but the main benefit will occur in other disciplines as in automobiles, railways, ships, surveying and personal mobility (figure 24).

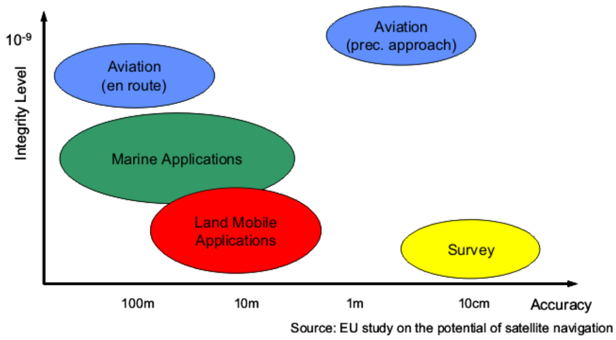


Figure 24: User requirements

An unconventional example is the prototype of an artificial guide dog (figure 25) to assist the navigation of visually impaired persons.

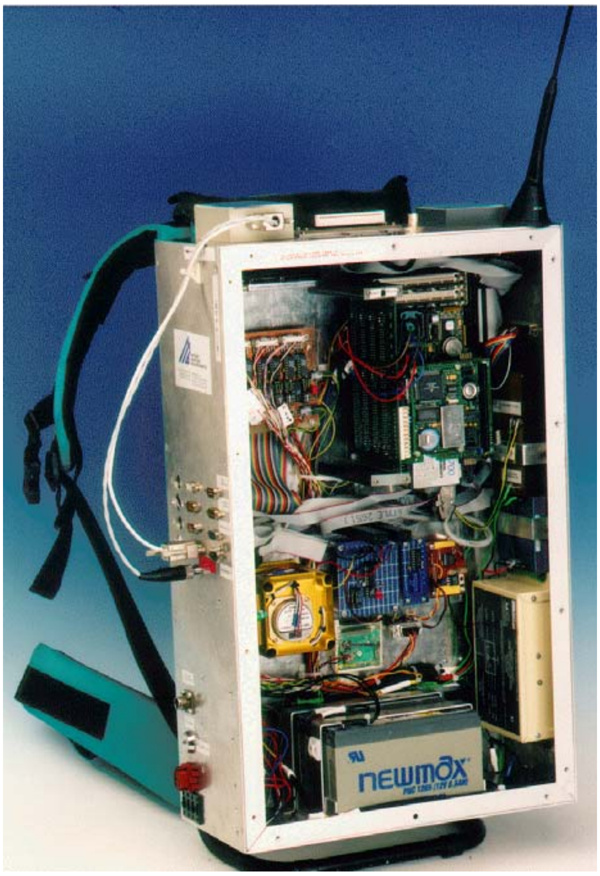


Figure 25: Personal navigator for the visually impaired

Precise positioning of an aircraft can be the basis for geodetically onboard measurement. In combination with an additional laser tracker a mountainous terrain covered with forest can be detected (figures 26 and 27). In combination with a high precision accelerometer the local variation of earth acceleration can be detected onboard of an aircraft (aerial gravimeter). This gravity measurement is of interest for many applications, e.g. mineral and water exploration, ballistic flight paths (figure 28).

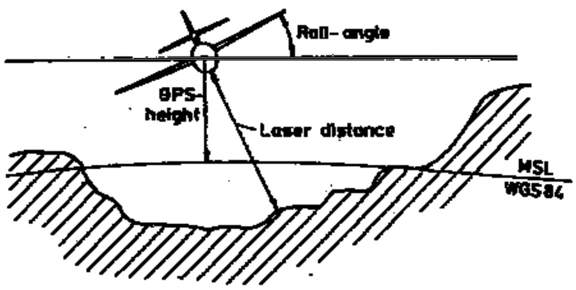


Figure 26: Contour measurement of mountainous regions (principle)

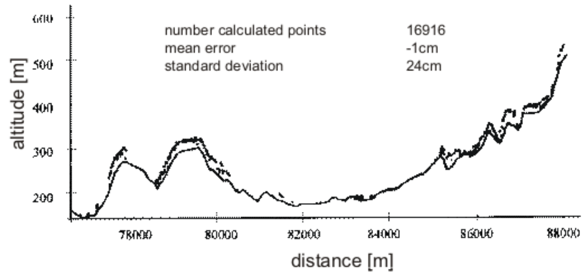


Figure 27: Contour measurement of mountainous regions (results)

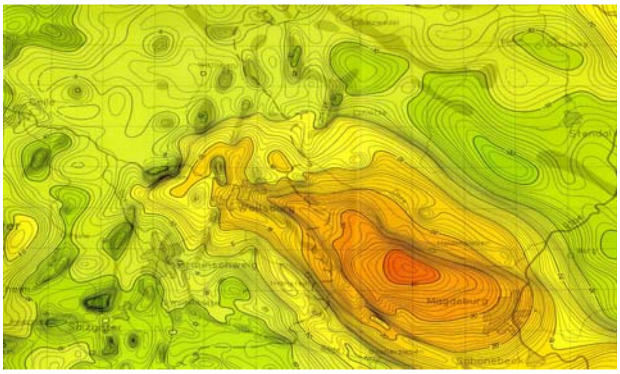


Figure 28: Earth’s Acceleration and Gravity Potential Contours

2 Aviation Safety

In our community we all know that air traffic has high degree of safety higher than other person traffic (figure 29). The risk to be killed in an automobile and in general aviation is roughly ten times higher as in standard commercial airplanes.

A typical average risk in a commercial airplane is one person killed in one billion passenger kilometers or roughly 2500 circles around the earth. As a human being has a better understanding of risk due to time, we can transform the traveling distance into flying time. With a typical airspeed of 500 km per hour, a person can fly in average 2 million hours before getting killed in the statistical sense, which is equivalent to 228 years.

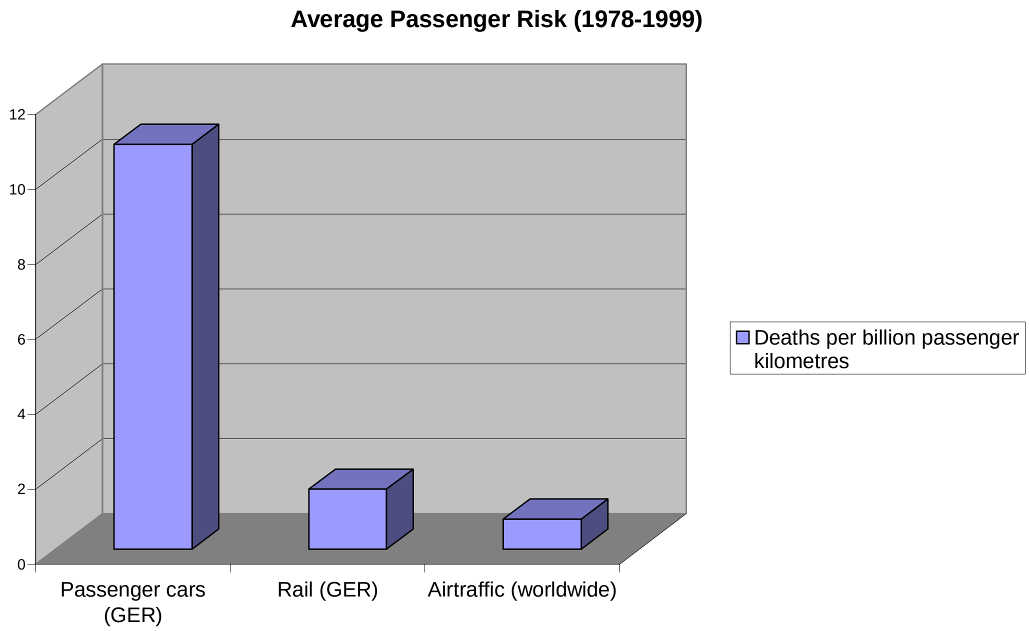


Figure 29: Average passenger risk

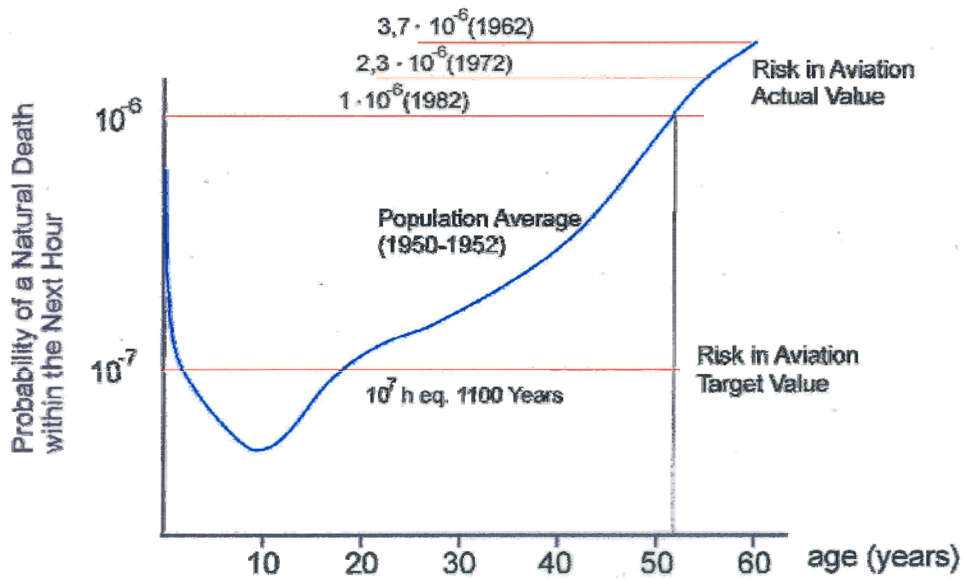


Figure 30: Probability of natural death

What is the acceptable target for aviation safety? As safe as possible? Then it is best not to fly. We all know that an aircraft designer as well as an airline operator has to find a compromise between economy and safety. An answer can give the probability of natural death of a human being (figure30).

The relevant data are collected from insurance companies in the United Kingdom. The lowest risk to die in the next hour is in an age of ten years. The living risk of a baby or a young child is higher. With an age of ten years, the probability of death smoothly increases without any significant changes of the slope. If we improve the failure rate by a factor of 5 to 10, then the achieved situation of a Target Level of Safety of 10^{-7} will be sufficient in my opinion.

The risk is depending from the flight phase (figure 31). Only 5 % of the total risk occurs in cruise flight, the major tasks of a transport aircraft. Roughly 95 % of all accidents occur in the vicinity of an airport: take-off and climb as well as descent and approach are involved with 59 %. The aircraft itself is the cause of the accidents with only 17 % (figure 32). The flight crew causes 56 % of all accidents. A consequence out of this situation is that we have to assist the pilots during approach and take-off.

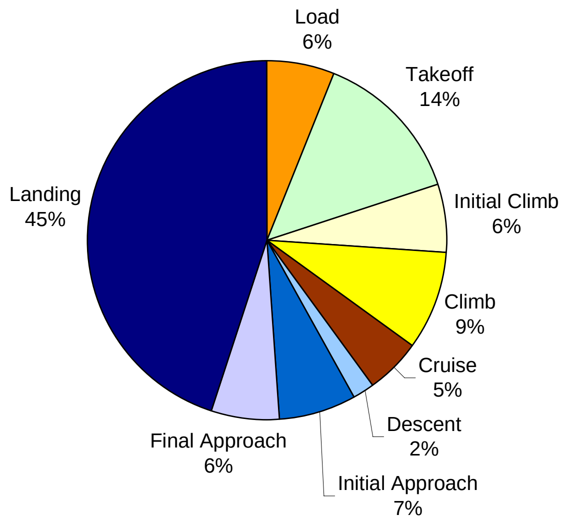


Figure 31: Total loss statistics according to flight phases

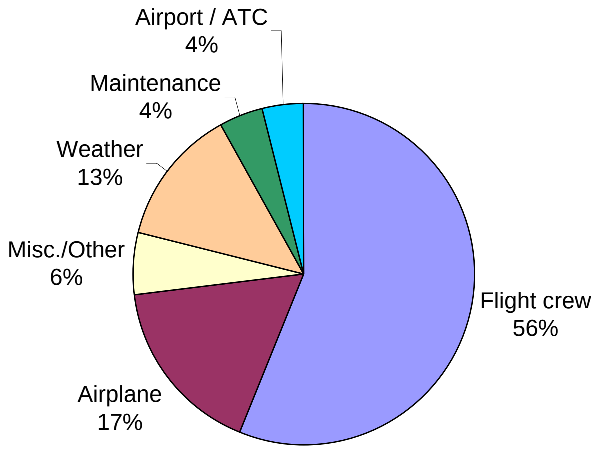


Figure 32: Total loss statistics according to causes

Figure 33 provides some directions on possible solutions. Displayed are the results of flight simulator studies where the pilots' workload in the different flight phases is compared with the pilots' performance ability. During long flights or a handicap, the pilots' performance will decrease. A handicap can be a cold or another light illness. If pilots' performance and workload are at the same level, the pilot operates at his limits and that is dangerous. A go-around is the most risky flight phase.

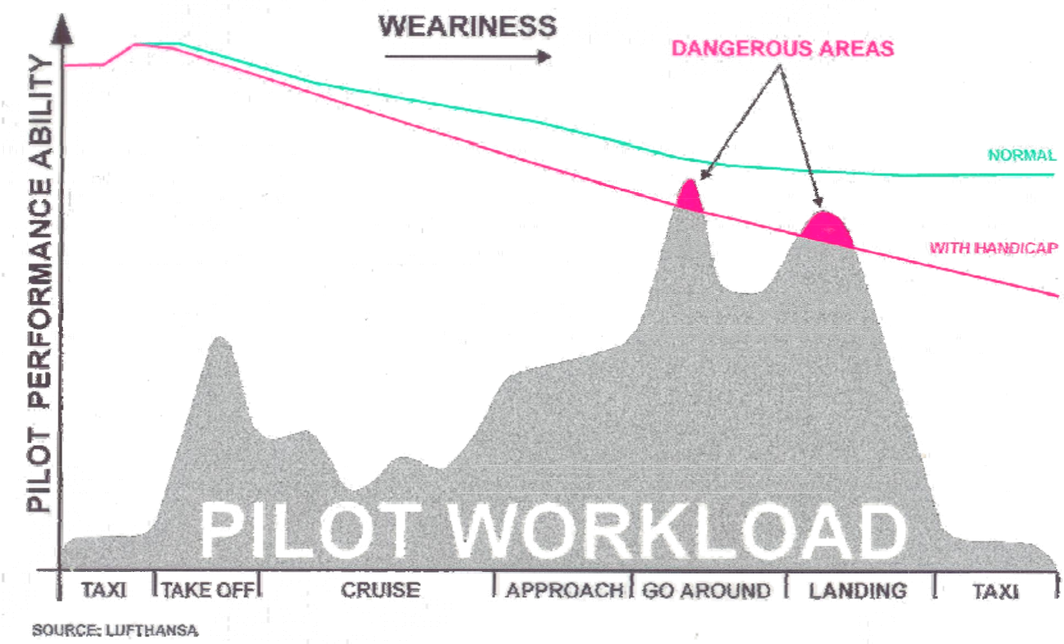
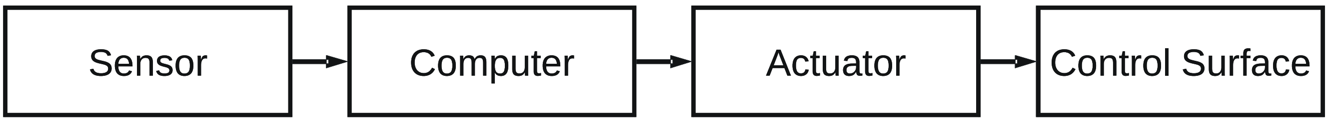


Figure 33: Performance ability and stress

An automatic flight control system for the risky phases of flight can assist the pilot and improve the aviation safety. The approach and landing under poor visibility conditions (e.g. CAT II/III) was the first target for investigations in safe flight control systems. In the mid sixties autoland systems have been developed in United Kingdom. In 1972, the first fully automated landing under real CAT IIIA conditions has been realized with a Trident aircraft at London Heathrow. The basic concept behind this fully automatic flight control system demanded a total aircraft failure rate better than 10^{-7} fatal accidents per hour. Generally, the requirement on guidance accuracy should be higher the poorer the visibility is.

If the required failure rate λ for the aircraft as a total system must not exceed 10^{-7} /h, then the subsystem of the flight controller is required to have a much smaller failure rate. A value of 10^{-8} / h is today accepted as target failure rate for subsystems. A flight controller consists typically of sensors, digital data processing units, actuator units and control surfaces of the aircraft (figure 34).

With a simple singular control chain and today's technology, failure rates of 10^{-3} per hour to 10^{-4} per hour can be achieved. First of all, I would like to take these abstract values and put them into perspective using experiences from every-day life. A failure rate value of 10^{-3} per hour indicates that a failure-free operation of the unit of 1000 hours can be obtained in the statistical mean. If you compare this failure rate with that of today's automobiles with a typical mean traveling distance of 100000 km, a mean traveling speed of 70 km / h and a resulting life-time of 1500 operating hours, then it should be clear that such an automobile should only experience one to two failures during its life time. However, we know from practical experience that this goal has yet to be achieved.
Although a flight control unit with a design failure rate of 10^{-3}/h can be regarded as "sophisticated and advanced" if compared to systems of every-day life –, there is a huge gap to the required failure rate of 10^{-8} / h. These small required values could only be achieved with today's technology and systems using the approach of redundancy (figure 35).



simplex: $A = \lambda \cdot t$ $\qquad \lambda = 10^{-3}$ / h
A...failure probability
λ...failure rate

Figure 34: Basic principle of a flight control unit (simplex control chain)

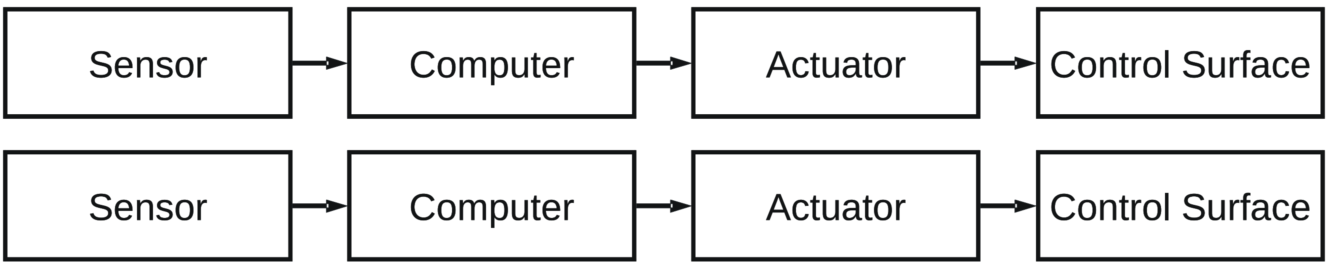


Figure 35: Duplex-control chain

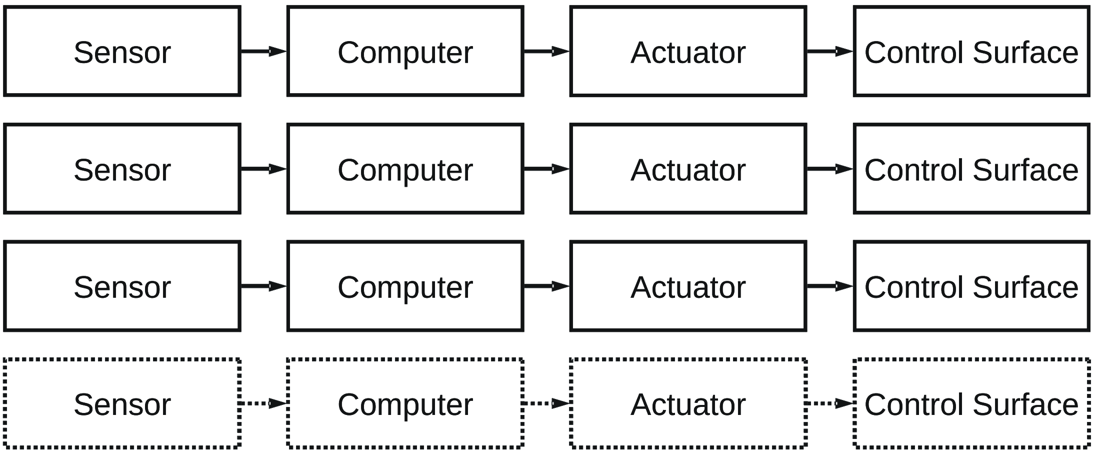
Figure 35 shows a duplex-redundant control chain. Both chains are designed to be identical. If the output of both these chains (here movement of the control surfaces of the aircraft) is identical within a certain failure tolerance, then the complete control chain will defined as operable. The failure in one of the control chains results in a difference in the output signals. A monitoring system detects this difference. However, it cannot identify the faulty subsystem. If such a monitoring system of a duplex-redundant control chain detects a failure, then the complete control chain must be de-activated. Hence, the control unit is not designed to be fail-operational and in the event of one single failure, the aircraft will not be controllable without the intervention of the pilot..

This behavior can be accepted for slow-reacting autopilots during cruise flight, where for certification it shall be demonstrated that within 12 seconds after the loss and de-activation of the control unit, the aircraft does not enter a dangerous state without the pilot's intervention. For older transport aircraft using simple flight controller units (e.g. in the General Aviation), these low gain control units are still in use.

Only if there are more than two parallel control chains, an identification and elimination of the faulty subsystem (here control chain) is possible (figure 36). The monitoring unit works using the "voting principle": if there is a difference between the output signals of the individual control chains, the output signal representing the majority will be selected and the output signal in minority will be neglected (so-called '*democracy principle*'). Using a triple-redundant control chain, there is still a duplex-redundant system remaining after the occurrence of the first fault.

The probability that the remaining duplex-redundant chain will also fail and the complete control chain must be de-activated is given now by:

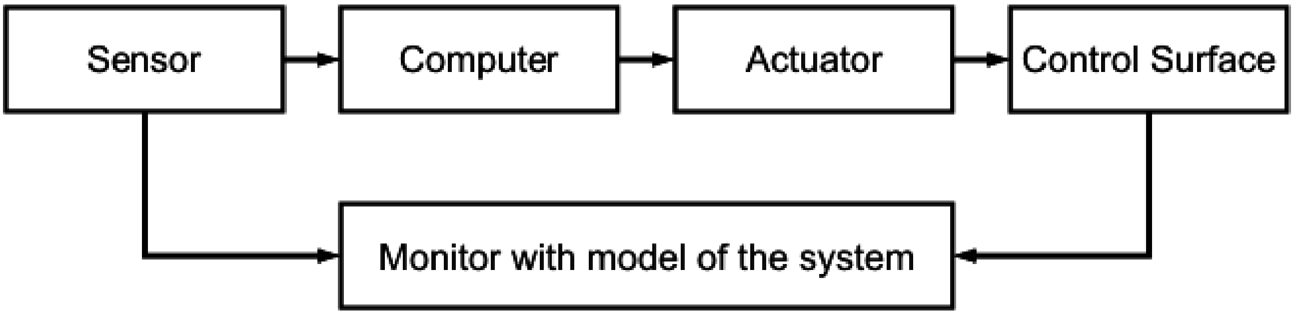
$$A = 3\lambda^2 t^2 = 3 \times 10^{-6}$$



simplex: $A = \lambda_{ind} \cdot t$ $A = 10^{-3}$
triplex: $A = 3\lambda_{ind}^2 \cdot t^2$ $A = 3 \cdot 10^{-6}$
quadruplex: $A = 4\lambda_{ind}^3 \cdot t^3$ $A = 4 \cdot 10^{-9}$

A...failure probability
λ...failure rate

Figure 36: Multiplex control chain



failure detection rate $K = 0.9...0.99$

Comparison of different control chains

Triplex: $A_{tri} = 3\lambda^2 \cdot t^2$ $\quad A_{tri} = 3 \cdot 10^{-6}$

Quadruplex: $A_{qu} = 4\lambda^3 \cdot t^3$ $\quad A_{qu} = 4 \cdot 10^{-9}$

Simplex self monitored: $K = 0.9$

$\lambda = 10^{-3} / h$

$A_{sim} = (1-K)\,\lambda\, t \quad = 10^{-4}$

Triplex self monitored: $A_{sim} = 3(1-K)^2\, \lambda^2\, t^2 \quad = 3 \cdot 10^{-7}$

Figure 37: Self-monitored control chain

However, this failure probability is still somewhat too high. In order to solve this issue, the following approaches can be applied:

Improving the technology of the individual control chain towards a design failure rate of 10^{-4} / h will result in a total failure probability of 3 x 10^{-8}, which is just below the requirements.

Alternatively, using a fourth chain (quadruplex redundancy) and a failure rate of 10^{-3} per hour for the individual chains, the failure probability of the complete control chain will be:

$$A = 4\lambda^3 t^3 = 4 \times 10^{-9}$$

This value is sufficient as well. A quadruplex-redundant system reverts to a triplex-redundant system in the case of a failure of one individual chain. This triplex-redundant system then is reduced to a still-operational duplex-redundant system at the occurrence of another failure.

The certification of 10^{-8} /h of a critical system with a designed failure rate is extremely difficult. By applying the approach of redundancy, the required failure probability of extremely rare events can be proven by mathematical analysis. The experimental prove is impossible due to the enormous time, which has to be waited in order to achieve statistically significant results. This should be instantly clear if one considers the fact that the average time between two failures is 10^8 hours or 10^5 years with 1000 test hours a year.

Even if simulations can nowadays be performed using extremely fast computers and digital data processing, then there is still the open question of the validity of the simulation methods to be answered.

An alternative option to simple control chains (figure 34) is given by the augmentation of such a control chain with a self-monitoring unit as shown in figure 37. This self-monitoring unit can contain a mathematical-physical model of the behavior of the control chain. In such a case, a comparison between the original control chain and the simulated model of the control chain will take place and if such a comparison detects significant differences, then the control chain system will be declared faulty.

In addition to the self-monitoring function, the formulation of such a mathematical model of the control chain and its simulation can provide additional functionalities, e.g. plausibility checks on other internal data. For example, the approach speed of a transport aircraft typically can be found in the range of 60 m/s to 90 m/s with mean values at 70 m/s. If the sensors provides a value which is outside of the tolerated range, it can be assumed that a failure occurred somewhere in the control chain. Based on that assumption, corrective measures can be taken (e.g. the de-activation of the particular control chain).

The effectiveness of the self-monitoring strongly depends on the creativeness of the design and consistency of the implementation. Using current technology, failure detection probability between 90 % and 99 % can be achieved.

The quantitative prove of the failure detection probability is almost impossible. However, a failure detection probability of 90 % can already decrease the probability of an undetected failure in the control chain significantly, in particular, if those self-monitored control chains are multiplied and integrated into a parallel-redundant system (figure 36)

The use of parallel redundancy, however, leads to several fundamental problems, which are both of technical and of philosophical origin.

In order to keep the effort for the mathematical verification of the failure probability requirements at a reasonable level, it is assumed that the elements of the control chain can be described using a constant failure rate. However, using comprehensive past experience, it is known that the failure rate is strongly dependent on time as a variable (figure 38)

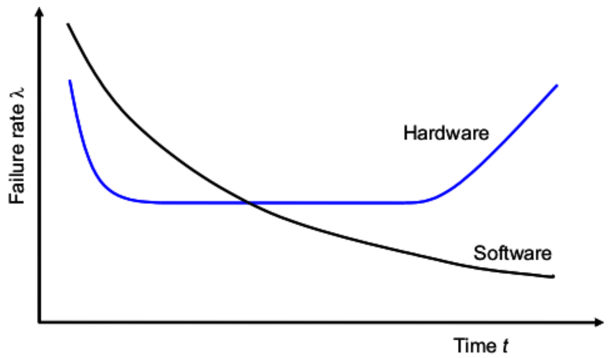


Figure 38: Typical failure rates of control systems hardware and software

The graph shown in figure 38 resembles a bathtub, and thus this particular form of function is referred to as bathtub curves. The relative high rate of failures at the beginning of the operating time is for the most part due to production or assembly errors. After that phase of early failures, an operation period of almost low constant failure rate commences, which is followed then by an increase of the failure rate due to aging and wear-out. It is noteworthy that a certain resemblance with the probability of natural death (as shown in figure 30) can be detected.

Thus, it follows from the above description for the operation of flight control units that these systems must be cycled through a testing phase before the deployment to operation in order to detect those early failures. During operation of the systems, those units which experience an increasing failure rate due to aging must be repaired or replaced.

Using a parallel-redundant system, the failure probability depends exponentially on the operating time (figure 37). Thus, the probability of a failure is marginal, if the operation time is short, but it will increase to an unacceptable level for longer operations. The operation time for an automatic landing is typically around a couple of minutes and only during this period, these extremely small failure probabilities are required.

The actual employment of an automatic landing system during approach and landing requires

additionally that all subsystems involved are completely functional at the beginning of this operation. The functional test to establish the usability of the subsystems must be completed in a very short period, since otherwise the already-tested subcomponents might fail in the meantime. The maximum-allowable period of time for those functional tests is in the range of one minute – and thus, it is obvious, that these functional tests can only be performed automatically.
Without a successfully passed functional test the system must be considered unreliable and must not be used. For example, a pilot must abort an approach at the height above ground of 30 meters in poor visibility conditions, if the functional test for the flight control units involved have failed. This decision to abort the approach and to initiate a go-round or to fly to an alternate airport requires discipline and consistency of the pilot in order to accept the inconveniences and the troubles of a missed-approach and of a landing at an alternate airport.
In contrast to the operation period of automatic landing systems the fly-by-wire system is always switched on when the aircraft is in operation. The requirements for total failure probability are therefore significantly higher. As already mentioned the introduction of fly-by-wire in commercial Airbus airplanes was a courageous but successful step.

Apart from the already-mentioned problems with the use of parallel redundant structures in aircraft, which are more of technical origin, still there are some basic issues of philosophical nature. The problem “Quis custodem custodit?“ was already known by the Romans. Then, it should come as no surprise that – even in technical and commercial applications – the monitoring of the monitor is even today only partly solvable.

Even a reliable test- and or monitoring system can interfere significantly with a fully-operational control system, e.g. through the de-activation of a functional control chain (i.e. a false alert) or through the non-detection of a fault in one particular control chain (i.e. a missed detection). Thus, these test- and monitoring systems are required to operate at an even-higher level of reliability than that of the monitored and test control chain.

Due to this requirement, only highly reliable sub-elements are used for the test- and monitoring units of flight controllers and a simple design with as few as possible sub-elements are implemented. This approach follows the general idea that the fewer components there are involved in a particular unit, the lower is the probability that the unit can fail in a certain operating period.

Until now we have only discussed randomly occurring errors and their elimination. However, much more unpleasant are systematic errors (also known as “common cause” errors) with which a flight control unit can be plagued due to inadequate design and implementation. Such systematic errors can be contained in a system without being obvious from the outset of the conception (dormant errors). Unfortunately, those systematic errors will only become noticeable under rare and unlikely circumstances. I would like to discuss such systematic errors using the following two examples.

Digital signal processing subsystems, which are nowadays typically contained in control chains, are in particular susceptible to systematic errors. With the current prevailing digital signal processing architecture, the signal-processing unit consists of both hardware devices (typically realized by a computer) and software programs.

Whereas the failures of the hardware devices are predominantly characterized by their stochastic nature, those of the software can typically be described as systematic and cause failures in most cases due to external circumstances which are outside of the normal operating environments. A typical example is the digital signal processing in a parallel-redundant control chain. If a failure in the digital signal processing causes an abnormal input-output relation, this can be found in all control chains – assuming that all these individual chains do contain the same digital signal processing programs. Now, a comparison of such a failed parallel-redundant system will not lead to a detection and isolation of the failure, since all redundant chains do contain the same failure mode and thus display the same failure behavior. A simple ´democratic´ majority voting ("*the majority is always right*") between the individual results will not reveal any failure, although all output signals are faulty.

The fundamental problem with systematic errors is the verification that the digital signal processing contains no such systematic errors. To my knowledge, there is no proven method for certification available. This fundamental issue can be attenuated, if the premise of identical output is waived and certification can be performed using tolerance regions (dissimilar redundancy). With digital signal processing programs, dissimilar redundancy can be achieved using the "n-version" programming, i.e. different groups develop the software independently without, hopefully, any relationship between them.

And if the safe prove of error-freeness cannot be executed, then this lack must be compensated using experience and plausibility checks. Using simulation techniques, all possible but known operating environments of an aircraft can be achieved and the resulting response behavior of the aircraft can be analyzed. This inherently very efficient empirical test approach is limited through the fact that no human being is so creative in defining all possible operating environments in order to analyze the response behavior of the aircraft. This lack in creativeness can only be overcome using increased experience, which must be gained through the analysis of events and accidents. However, this experience is hard-gained, since those events and accidents occur – by their very nature – only in rare circumstances.

The following examples will show that systematic errors are not predominantly occurring in software programs, but can be caused as well by erroneous or inconsistent design. Wide-bodied transport aircraft do have in general a quadruplex-redundant hydraulic supply and control units for the safety-critical control surfaces such as elevators. With aircraft powered by four-engines, each of the engines power supply generator will be connected to one of the hydraulic supply and control chains, thereby establishing and ensuring a quadruple-redundant control unit. If one of the engines of the aircraft fails, then – by consequence – one of the hydraulic control chains of the elevator will fail as well. For short periods of time, an electric hydraulic pump connected to a battery is used in bridging the hydraulic supply.

However, with aircraft powered by two engines the situation is much worse. In a quadruplex-redundant elevator control unit, the failure of one aircraft engine will cause two failures in the control chain of the elevator, thereby disabling not only one, but two individual control chains. Thus, if an aircraft powered by two engines contains higher-redundant control units, an independent energy supply in the form of an Auxiliary Power Unit (APU) able to work in flight must be provided.

Such problems are obvious and can be easily identified and solved by experienced engineers. Unfortunately, there are examples where the creativeness of the aircraft design engineers was not sufficient to identify all possible existing problems for systematic errors. The circumstances that caused the catastrophic accident described below were beyond conception.

The design of a wide-bodied commercial transport aircraft (here DC10) requires an enormous effort in order to achieve the required extremely small failure probability for all critical units. The hydraulic elevator control units were designed using quadruplex redundant implementations, so that the aircraft is controllable even in the event of two failures in different control chains. In order to supply the hydraulic actuators for the elevator control surfaces in the tail of the aircraft, four hydraulic pipelines are installed under the floor of the passenger compartment. During a flight from

Ankara to Paris (1974), the aircraft lost a door to the freight compartment due to design failures and operational errors. It is well known that the aircraft cabin is pressurized for the health and the comfort of the passengers – the cabin pressure is in typical cruise altitudes higher than the ambient pressure. With the loss of the door to the freight compartment, there was a sudden de-pressurization of the aircraft cabin. The resulting pressure difference between the freight compartment and the passenger compartment put too much load on the cabin floor so that it fractured and – at the same time – destroyed the four hydraulic pipelines. With the loss of all four hydraulic actuators, the aircraft was uncontrollable and crashed.

Thus, the overall redundancy concept was invalidated through only one systematic design error – the installation of all hydraulic supply pipelines in the same place. The design engineers of the control units were not able to conceive that the cabin floor might be fractured due to whatever cause. The same effect would have taken place in the case of a bomb explosion in the tail of an aircraft.
Due to that catastrophic experience, the hydraulic pipelines in modern transport aircraft will be dissimilarly distributed along the aircraft body surfaces. Incidentally, this technique has been long in use for military aircraft, since a failure of one hydraulic control chain due to combat damage must not incapacitate the whole aircraft.
Furthermore, pressure valves are built into the cabin floor in recent transport aircraft in order to avoid the loos of the cabin floor in the case of a pressure loss. Here, care must be taken to avoid eliminating one systematic design error by introducing another systematic design error. In the case of a fire in the freight compartment, it must be prevented that toxic gases can infiltrate into the passenger compartment. At least for one wide-bodied aircraft powered by two engines (Airbus), these design modifications have participated to avoid a catastrophic hull loss when the tail of the aircraft body was partly destroyed by a terrorist bomb attack.
It is state of the art to equip modern transport aircraft with safe redundant autoland systems. To my knowledge, there is worldwide no fatal accident reported for real CAT III and CAT II landings. This leads to the paradox situation that landings under poor visibility conditions (blind landings) are safer than landing in good visibility.

The increase in automation in aircraft guidance has changed the role of the pilot. In former times, he was the admired hero, but nowadays the pilot is more the general manager who operates the aircraft safe and efficient with displays, computers and communications.
A full automatic system has a limited ability to respond to unknown situations. The designer of the automatic system can never plan to forecast all unforeseeable situations. In my opinion, the guidance will even in future be a compromise between the consequent and safe operation of the automatic system and intuition of the human being. The role of the pilot becomes more and more comparable to that of a controller in the industrial and economical sense.

3 Response of Aircraft in Disturbed Atmosphere

Since the beginning of aviation, the response of airplane in the gusty and turbulent atmosphere was problematic and dangerous. Especially those airplanes with low static stability or poorly damped phugoid motion and Dutch roll were difficult to control. Lilienthal lost his life in a crash into the ground as a result of a gust response. In one century of scientific investigation a lot of fundamental and practical research concerning the atmosphere as well as the response of aircraft due to the atmospheric disturbances has been done. In the last decades the research activities concentrated on self-made wake vortices (figure 39), as this phenomenon is the biggest economical obstacle for airport capacity and economy

Figure 39: Wake vortices behind aircrafts

V... Airspeed
V_K... Groundspeed
V_W... Windspeed

Figure 40: Aircraft in disturbed atmosphere

All the atmospheric disturbances produce primarily a local and time dependent variation of wind speed V_w in the atmosphere (figure 40). If the aircraft passes the atmosphere with the inertial (ground, flight path) speed V_k then the airspeed V is the superposition of both.

$$\underline{V} = \underline{V}_k - \underline{V}_w$$

As the wind speed varies with position and time, at all parts of the airplane we obtain different local air speed (figure41).
The scale of the turbulence wavelength L_W in relation to a typical dimension of the aircraft L_a is responsible

$$R = \frac{L_w}{L_a}$$

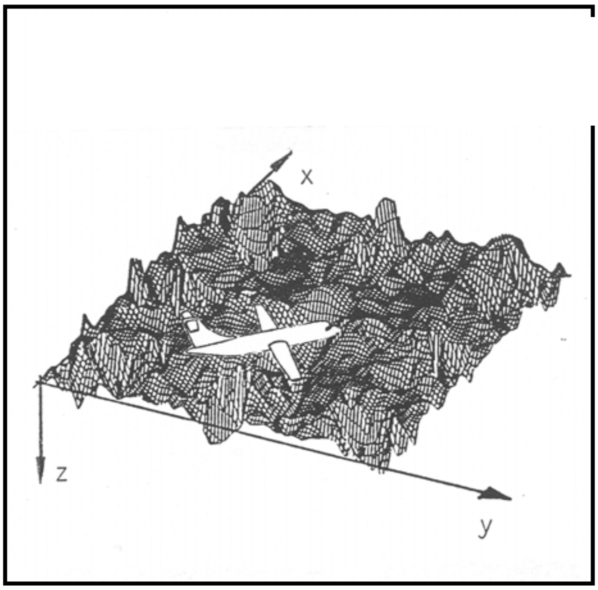


Figure 41: Airplane passing a two-dimensional turbulence field

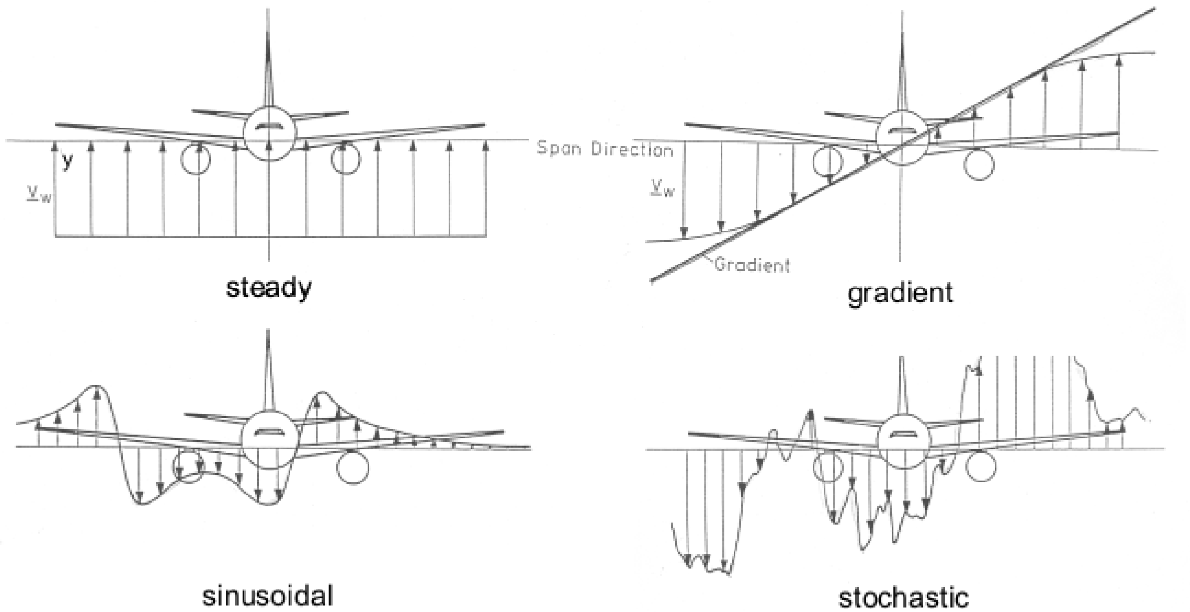


Figure 42: Local airspeed distribution when passing different basic wind and turbulence fields

for the aircraft response. The atmospheric wavelength L_w may be the average wave length (integral scale) for turbulence that varies with height and atmospheric stability (Richardson number), diameter of a thunderstorm or a wake vortex (figure 43 and figure 56). Typical airplane parameters at the mean aerodynamic chord $\bar{c}$, the span s or the phugoid wave length L_p.

The basic aircraft response in gust, turbulence, wind shear and wake vortices can be simply separated into three typical frequency regimes

- High frequency wind changes result in high frequency air speed variation followed by high frequency aerodynamic forces and moments. These forces initiate aircraft acceleration.
- In low frequency wind variation, the airspeed is relatively constant due to static stability of the aircraft. The aircraft flight path speed will be varied with wind speed.
- The changeover frequency between those two states is roughly that of the phugoid motion.

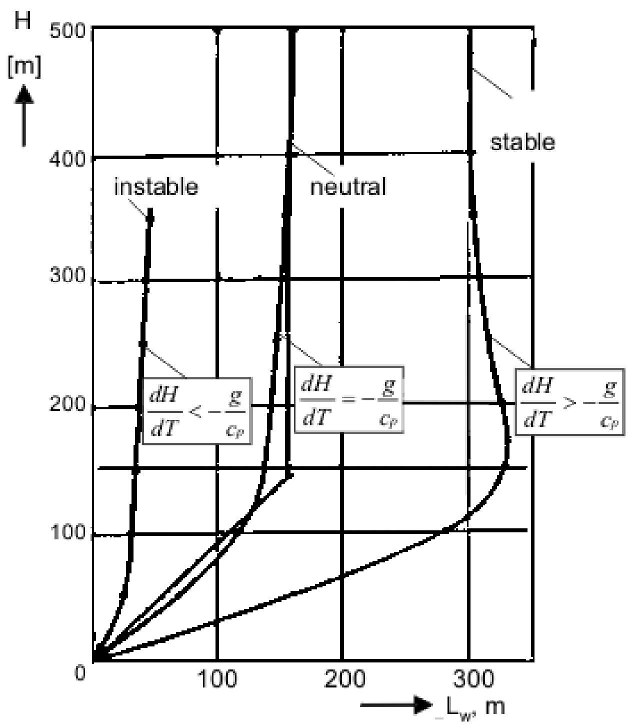


Figure 43: Integral scale L_w as a function of height and stability of the atmosphere

A well-known example is the response of local lift due to a step input of a vertical gust (figure 44). The unsteady dynamic response is known as Küssner-Effect (1926). The lift response depends on Mach number and aspect ratio. With modern control theory this response can be transformed as transfer function to any other form of input, e.g. stochastic. Since Küssner, only little research has been done in this domain. Especially for real time simulation, e.g. landing, better aerodynamic dynamic models would be helpful.

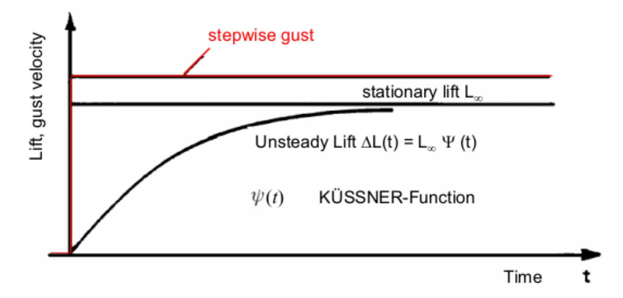


Figure 44: Unsteady lift response as a function of a stepwise gust (Küssner 1926)

The metrological society has developed sufficient models of the atmosphere. Especially just after the first and the second World War the knowledge has been extensively developed forward by scientists who where not allowed to work in their own domain, e.g. aerospace or nuclear power.

The turbulence spectrum is well accepted in the vicinity of the inertial sub-range (figure 45). A slope of the power density spectrum in the inertial sub range have been calculated by Kolmogorov (1941) to be $\Omega^{-5/3}$. In the short wave length domain (large spatial frequency Ω, dissipation of the vortices) the slope of the spectrum is not quite clear. The consequent application of Kolmogorovs (1941) formulation gives unsolvable mathematical and physical problems. For practical use, Theodor von Karman has derived a spectrum-formulation that fits the inertial sub range and the break-frequency fairly well. Outside the inertial sub range the formula of *von Karman* leads to unrealistic results. The simple formulation (in the mathematical sense) of the turbulence power-density arranged by Hugh L. Dryden give sufficient results in the inertial sub range, but outside the inertial range this formula is as unrealistic as von Karmans formulation, but much easier to handle in computer calculation.

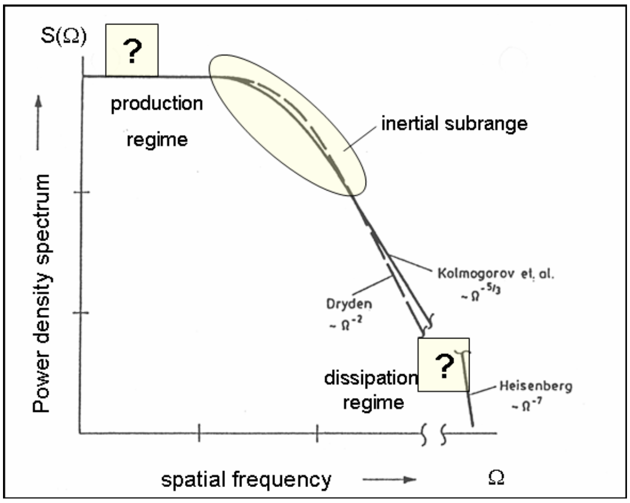


Figure 45: Turbulence power density spectrum

The measurement of large wavelengths is extremely difficult and the knowledge is sparse. If we accept Kraichnan´s theory that turbulence consists of vortices of different dimensions then we will find that the maximum vortex diameter is in the size of the atmosphere itself. A typical atmospheric scale parameter is the height of the tropopause in an elevation of approximately 11 km. Close to the ground the effective wavelength L will increase with height (figure 46).

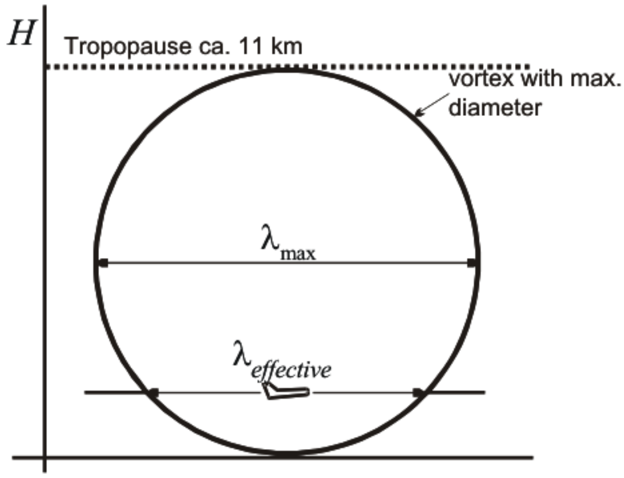


Figure 46: Effective and maximum turbulence wavelength.

The smaller the wave length parameter L_w/c, the higher is the turbulence frequency and the stronger is the effect of unsteady aerodynamic flow and therefore the gust alleviation effect. In the definition of control theory the unsteady lift responses as low pass filter.
This turbulence ground effect demonstrate figures 47and 48.

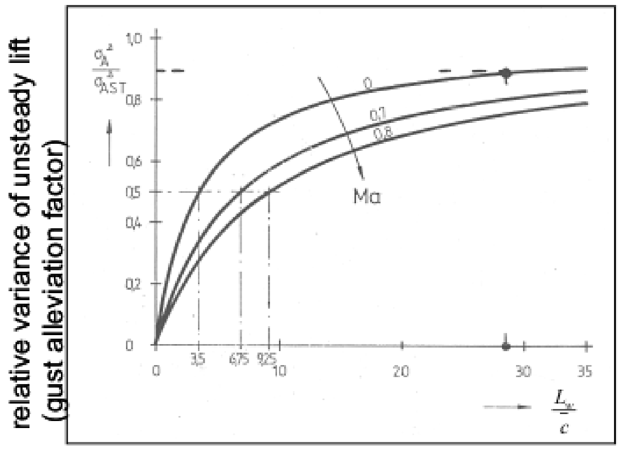


Figure 47: Gust alleviation factor as a function of relative integral scale L_w/c .

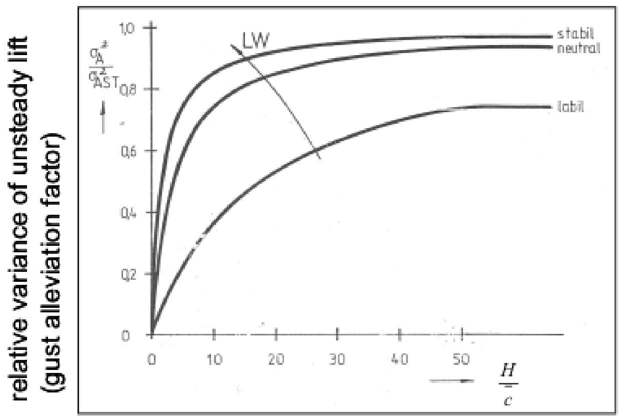


Figure 48: Gust alleviation factor as a function of relative height above ground

For a typical large transport aircraft with a mean aerodynamic chord of $\bar{c}$=6m for in the height domain below 50m, always unsteady aerodynamic forces have to be taken into account for the mathematical analysis and simulation. Otherwise we get a hard landing in the simulator (by neglecting the gust alleviation effects), but a soft landing in reality.

Aircraft response in turbulence is more or less a flight mechanical and aerodynamic problem with some interference to fatigue lifetime. Many interesting questions are still waiting for sufficient answers.

In contrast to turbulence and gust response the flight in wind shear and thunderstorms affect aviation safety to a higher degree. A typical turbulence response occurs primarily in the high frequency regime, where the typical wind shear response of an aircraft is based in the low frequency regime. Nevertheless low frequency turbulence can occur (see figures 45 and 46). A low frequency is typically the phugoid frequency or even lower. It is well known that an aircraft converts its potential energy into kinetic energy and vice versa at approximately constant total energy in the phugoid frequency regime. Dynamic variation of potential energy causes heavy flight path deviations. There are some indications that a human pilot cannot observe such low frequencies. This unsolved man-machine problem has a reasonable potential for fatal accidents.

Take off or approach in wind shear or thunderstorm conditions can be fatal if the pilot is not adequately trained for this weather phenomena. The typical response of an aircraft shall be demonstrated with a wind shear layer where the wind speed will be changed linearly. In figure 49 the aircraft passes in landing approach the shear layer of a thickness of 50 m. The wind speed will change from 12.5m/s to zero or vice versa. The wind shear gradient is significant with

$$\frac{dV_w}{dh} = 0.25\frac{1}{s} = 16{,}6\frac{kts}{100\,ft}$$

In head wind shear the aircraft will overshoot the desired flight path and in tail wind shear the aircraft will execute an under shoot. Thus, the changing wind shear conditions will initiate an oscillation of the phugoid mode with a wavelength of Lph=2km at typical approach speed. The oscillation time is 30s. The greatest deviation from the flight path is 130m and occurs outside of the shear layer. The most dangerous situation takes place if the shear is positioned in an altitude between 100 and 150 m. In this case, the aircraft crashes into the ground, if the pilot or the autopilot will not interfere.

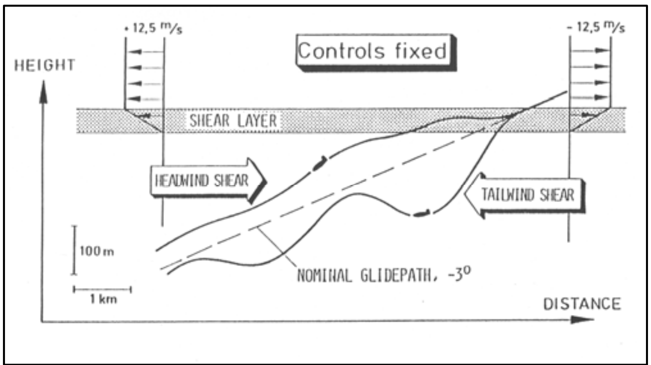


Figure 49: Typical aircraft response in a wind shear layer

The statically stable airplane will keep the airspeed constant. The pilot or an automatic flight control system can assist this behavior. If the air speed will keep constant, then

$$\underline{V} = \underline{V}_k - \underline{V}_w \quad \Rightarrow \quad \dot{\underline{V}} = \dot{\underline{V}}_k - \dot{\underline{V}}_w$$

Constant airspeed results in $\dot{\underline{V}} = \underline{0}$ and therefore

$$\dot{\underline{V}}_k = \dot{\underline{V}}_w$$

In a landing approach guided by an instrument landing system, the flight path deviation is small (Δγ=0). With constant airspeed the variation of the drag to lift ratio is zero.

$$\Delta \frac{T}{W} = \frac{\dot{V}_w}{V}$$

The required thrust $\Delta T/W$ variation is presented in figure 50 for consequent application of the formula and as well as for realistic constraints for limited throttle activities. The same control law can be applied in the fatal thunderstorm accident of a Boeing 727 aircraft in New York in 1975. In the manually executed approach a significant under shoot results even when an experienced pilots was flying. The airspeed is approximately constant due to sufficient static stability.

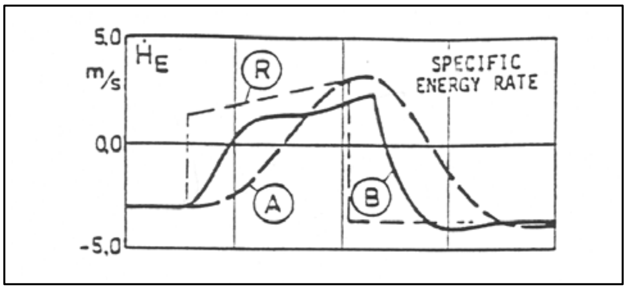


Figure 50: Required thrust (especially specific energy rate) in the wind shear of fig.49. -
R required specific energy rate, A conventional automatic flight controls (low throttle activity, B specific energy rate management

The required thrust will be demonstrated in a phase diagram in figure 51 where thrust rate versus thrust is plotted for the automatic approach. The straight lines in figure 51 indicate the operational constraints of the engine. Neither maximum thrust rate nor maximum thrust will be touched. With adequate flight control this accident could have been avoided. The question why an experienced pilot differs significantly from an ideal flight control system is difficult to answer and a serious man-machine problem.

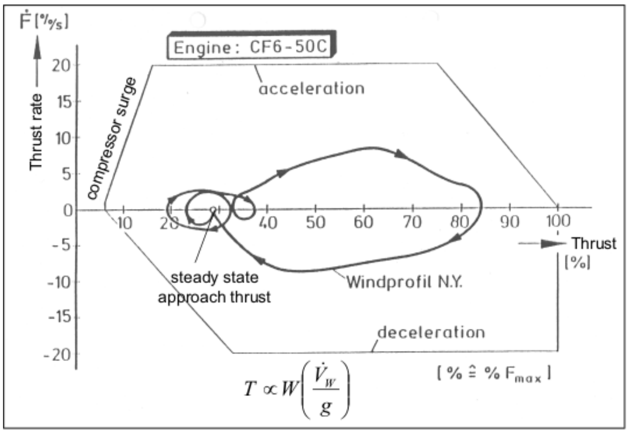


Figure 51: Phase diagram of required thrust in a simulated thunderstorm accident (B727, New York 1975)

The heaviest reported wind shear that caused a fatal aircraft accident was that of Khabarovsk (Sovjetunion) in 1975. The reported and reconstructed wind velocity Vw versus height H is plotted in figure 52. The maximum wind shear gradient exceeds

$$\frac{dV_w}{dh} = \frac{21m/s}{70m} = 0.3\frac{1}{s} = 17{,}8\frac{kts}{100\,ft}$$

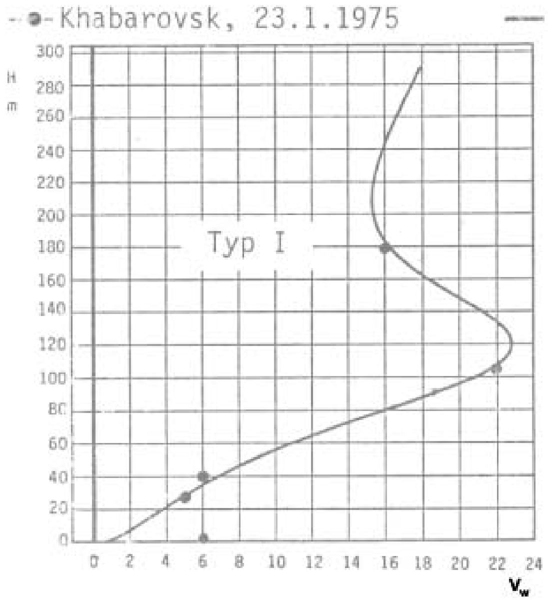


Figure 52: Strong wind shear in Khabarovsk (1975) causing a Fatal Accident

The simulated aircraft response is presented in figure 53 for manual and automatic approach as a function of distance to threshold.

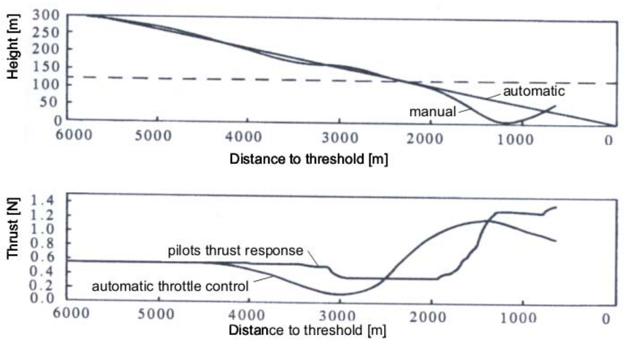


Figure 53: Simulated flight path and thrust response for the fatal Khabarovsk wind shear

The automatic flight controller keeps the flight path deviation small, but in the manual approach the aircraft will touch the ground 1200m in front of the threshold.

The thrust response for an ideal controller during a manual approach is in principle similar but in manual approach we obtain some digitized response of the pilot and a time delay of the pilots thrust signal compared to the automatic controller of roughly 30 s. Different flight-simulators operated with ten individual pilots and a variation of heights for maximum wind speed gave delay time in a domain between 25 and 40 seconds. The reason for this enormous delay was not clear at that time.

An artificial neural network (figure 54) is in principle more related to a human being than a conventional flight control system with a fixed structure. The inputs for this neural network are air speed, rate of descend, flight path deviation and barometric altitude and the output is thrust variation.

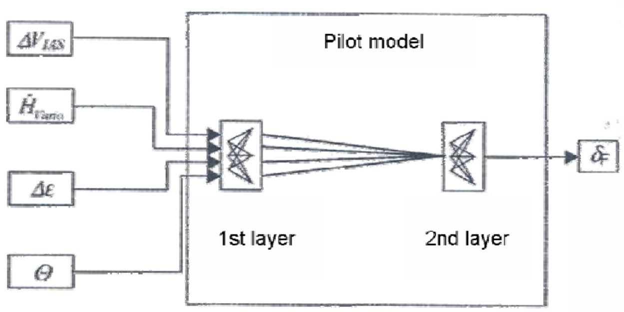


Figure 54: Artificial neural network architecture for a thrust control system.

The neural network had been trained in 100 approaches in the Khabarovsk wind shear (figure 52) environment. The result, not unexpected, was identical with the optimal conventional flight control system. Neural networks can give the same excellent results as the conventional flight control systems, if properly designed.

When designing a conventional flight control system, excellent knowledge of the airplane dynamics is required. A neural network learns the flight mechanical lessons by trial and error. But the behavior of a neural network especially in safety critical applications is difficult to predict. Therefore no certification procedure for this type of controller will exist. But to validate results of conventional flight control systems, neural networks can be very helpful as this structure of controller is totally dissimilar.

As both automatic flight control systems, conventional as well as neural networks gave similar results and this differed very much from the pilot's behavior, we had still no answer why a human pilot had such big problems in a wind shear situation.
After some discussion we came to the result that our training procedure (for the neural network) was too specific and thus too unrealistic. A human pilot will never be trained only for one specific wind shear approach. He starts his pilot career as a pilot student in a flying school. He learns first to control the rotational axis roll, pitch, and yaw of the aircraft and second to control altitude and airspeed. To navigate the airplane and to control a landing approach are the next lessons to learn. In a special course the pilot will learn to operate in wind shear situations.

The neural network, trained in the similar procedure as the student pilot had a similar behavior compared to a pilot, especially in wind shear. We found a similar delay in throttle response, approximately half the delay time but similar shape. With the two different trained neural network controllers, the type human pilot type of neural network and the neural network type for ideal wind shear controller we were able to identify the differences. The only remarkable difference was a low gain integral feed back of air speed deviation that was not available at the human pilot model. The time integral of the airspeed deviation is more or less a measure of the dynamic energy deviation of the airplane.
With an additional total energy indicator, the human pilot will be able to apply a sufficient throttle control, thus achieving a safe approach in wind shear situations. This computer assisted manual throttle control gives results that are just as good as an automatic control.

This example demonstrates that the man-machine-problem is of major importance for aviation safety and a lot of additional research is required to understand and to solve these problems.

4 Wake Vortices

The creation of the required lift for a flying aircraft is always accompanied by vortices (figures 39 and 56). These vortices have the effect of small tornadoes deteriorating the flight path of a passing aircraft very much.

Figure 55: Wake vortex impression

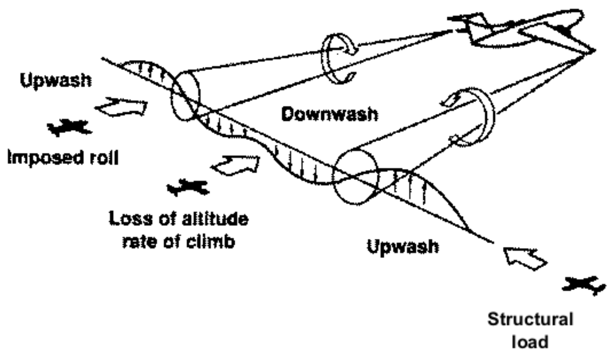


Figure 56: Response of aircraft when passing a wake vortex

The situation can be dangerous for following aircraft if the rolling moment of the vortex will initiate a significant rolling motion. A full 360° roll of medium sized passenger aircraft of 100 passengers behind a heavy aircraft loaded with 400 passengers have been observed several times. During landing approach even slight wake vortices can deteriorate the flight path of bigger airplanes (figure57).

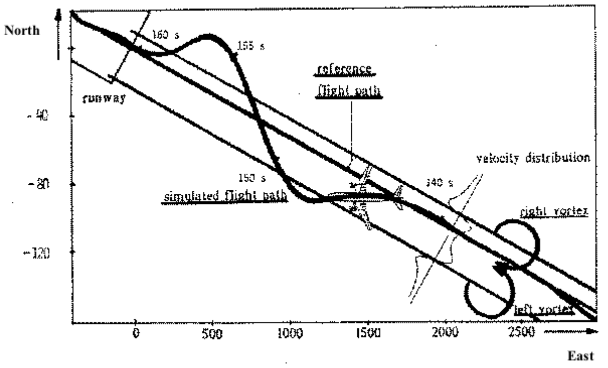


Figure 57: Simulated wake vortex encounter during final approach

The generation of the vortex and its lifetime is complex and not fully understood up to now. It's agreed that the vorticity Γ is a sufficient measure of the strength of the vortex (fig. 58). Following the famous Kutta-Joukowski-formula, the vorticity is proportional to the weight of an aircraft related to wing span s (or more precise the distance s` between the two wingtip vortices) and airspeed V. The heavier an aircraft the stronger is its wake vortex.

The time dependent development of a vortex is a complex process, which can be differentiated into roll-up, aging and decay. Just behind the aircraft the roll-up stage starts and the wake vortex develops. Then the aging begins. The aging process is depending on the aerodynamic design of the airplane and much more from the status of the atmosphere. High intensity of turbulence (σ_W) and unstable conditions of the atmosphere (positive Richard number R_i) accelerate the aging of the vortex (figures 58 and 59). A stable undisturbed atmosphere is responsible for a long lifetime of the vortex. In the decay stage the vortex is harmless. But to understand the aging process of a vortex, additional intensive research will be required.

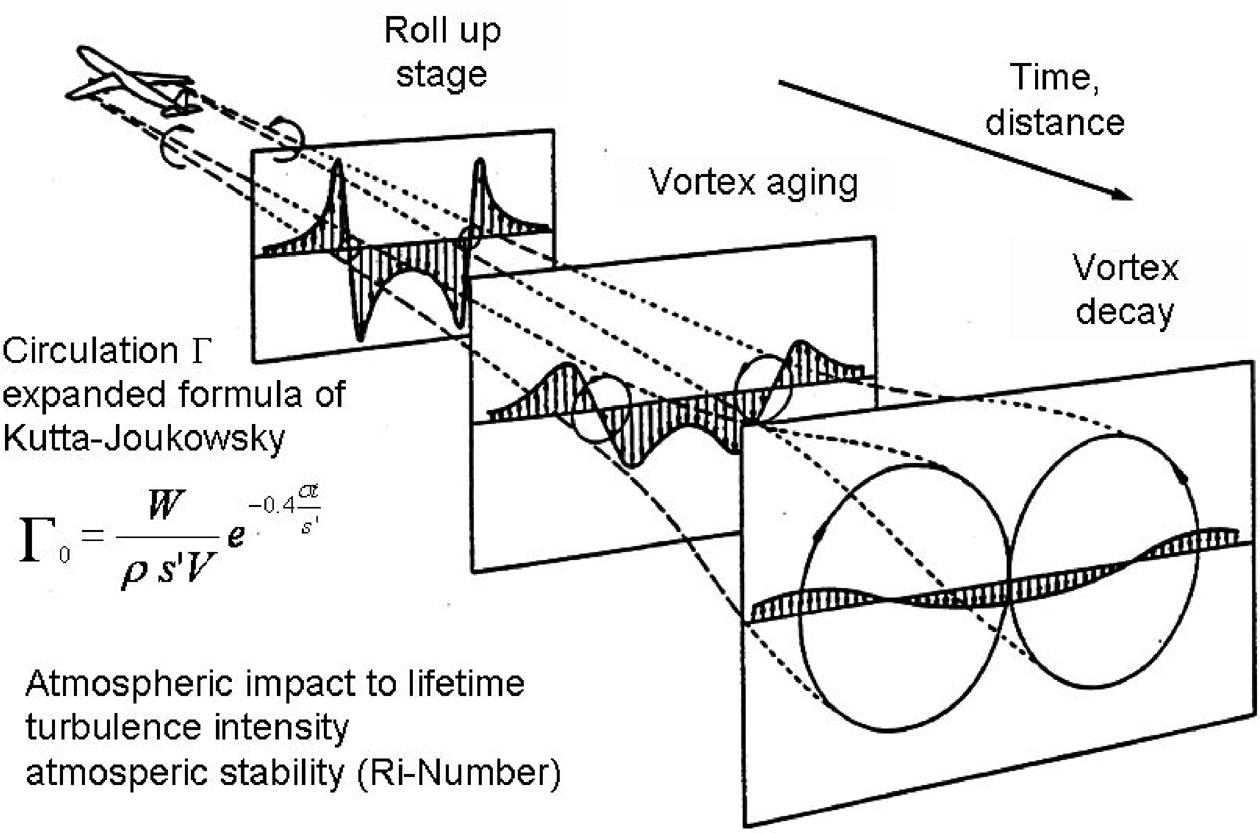
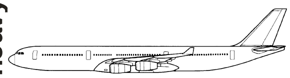
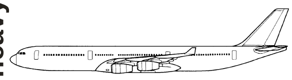
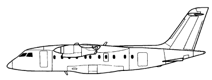
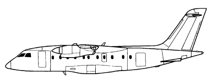


Figure 58: Evolution of a wake vortex

Figure 59: Rollup and decay of a wake vortex

Weight categories		Separation distance [nm]	Separation time [s] @ V = 70 m/s
leading aircraft	following aircraft		
heavy 	heavy 	3	80
	medium 	5	132
	light 	6	159
medium 	light 	4	106

heavy: > 136t , medium: 7 - 136t , light: < 7t

Figure 60: ICAO wake vortex separation classes

A flight into a vortex is safe if the separation distance between two airplanes is large enough so that no significant reaction of the following aircraft will occur. The relevant separation distance between two aircraft is primarily depending on the actual weight of the two involved aircrafts. The maximum take-off weight is an easy measure but is not relevant, especially for long distance airplane. The maximum take-off weight of airplanes is separated in three categories (figure 60): light, medium and heavy.

The separation time results of a combination of the categories. This separation is based on experience but it is very coarse. The separation is primarily responsible for the landing frequency on a runway. With a typical separation time of two minutes thirty landings per hour can be realized on one runway (figure60).

The separation time due to wake vortices is the biggest obstruction for airport and runway economy. There is potential to reduce the separation distance by more adequate weight categories and to take into account the atmospheric conditions for the vortex lifetime. The instruments and the computer power are available. But even with the present wake vortex separation procedure a dangerous vortex event can appear in rare cases. In general a detection of the vortex by radio waves, light or sound using the RADAR principle is feasible, but intensive research is required.
In my mind the highest economical gain in commercial air transport is a more efficient use of the runway. The wake vortex is the biggest

problem that has to be solved. Flight guidance and control on ground as well as in the aircraft can develop tools to approach this target. There is a real need that airport operators, air traffic control organizations, airlines and aircraft designers will come to common sense to improve the present situation.